ADA019026

(12)

Technical Report

R 828

Sponsored by

DEPARTMENT OF THE ARMY
PICATINNY ARSENAL

November 1975

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

BLAST ENVIRONMENT FROM FULLY AND PARTIALLY VENTED EXPLOSIONS IN CUBICLES

By

W. A. Keenan and J. E. Tancreto

Approved for public release; distribution unlimited.

A

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TR-828 (14) CEL-TR-828	2. GOVT ACCESSION NO. DN244065	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) BLAST ENVIRONMENT FROM FULLY AND PARTIALLY VENTED EXPLOSIONS IN CUBICLES.		5. TYPE OF REPORT & PERIOD COVERED Final; Jun 1971 – Jun 1974
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) W. A. Keenan, J. E. Tancreto		8. CONTRACT OR GRANT NUMBER(s) (12) 155 p.
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY, Naval Construction Battalion Center, Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ~~Army MIPR; 51-027~~
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army, Picatinny Arsenal, Dover, New Jersey 07801	(11)	12. REPORT DATE November 1975
		13. NUMBER OF PAGES 113
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(9) Final rept. Jun 71 – Jun 74

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Explosive storage, explosive effects, dynamic structural analysis, cubicles, magazine, blast pressure.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Charges of cast cylinders of composition B explosive were detonated inside several small-scale 3- and 4-wall cubicles of different shape and size to establish methods and criteria for predicting the blast environment (positive and negative pressures, durations, and impulses) in and around cubicles containing fully and partially vented explosions. The blast environment was measured (1) inside the cubicle and (2) outside the cubicle behind the Next page

continued

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391 111

20. Continued

front wall, sidewalls, and rear wall at scaled distances from 1.42 to 63.0 ft/lb$^{1/3}$. The blast environment was found to depend on the charge-to-volume ratio, scaled degree of venting, scaled vent area, and scaled distance. Design charts are presented for calculating the pressure-time loading in and around a cubicle for a wide range of these parameters. The procedures offer, for the first time, a rational procedure for tailoring the cubicle configuration and dimensions to the site requirements since it relates blast environment to cubicle parameters and charge weight. Some of the 3-wall cubicles had roofs and some did not. Adding a roof did not substantially reduce the blast environment at large-scaled distances. The greatest benefit from the roof was in the area close to the cubicle where the roof dramatically reduced the blast environment behind the backwall.

Criteria is proposed for design loading in and around fully and partially vented cubicles.

Library Card

Civil Engineering Laboratory
BLAST ENVIRONMENT FROM FULLY AND PARTIALLY VENTED EXPLOSIONS IN CUBICLES (Final), by W. A. Keenan and J. E. Tancreto
TR-828 113 p. illus November 1975 Unclassified

1. Explosive storage 2. Blast pressure I. 51-027

Charges of cast cylinders of composition B explosive were detonated inside several small-scale 3- and 4-wall cubicles of different shape and size to establish methods and criteria for predicting the blast environment (positive and negative pressures, durations, and impulses) in and around cubicles containing fully and partially vented explosions. The blast environment was measured (1) inside the cubicle and (2) outside the cubicle behind the front wall, sidewalls, and rear wall at scaled distances from 1.42 to 63.0 ft/lb$^{1/3}$. The blast environment was found to depend on the charge-to-volume ratio, scaled degree of venting, scaled vent area, and scaled distance. Design charts are presented for calculating the pressure-time loading in and around a cubicle for a wide range of these parameters. The procedures offer, for the first time, a rational procedure for tailoring the cubicle configuration and dimensions to the site requirements since it relates blast environment to cubicle parameters and charge weight. Some of the 3-wall cubicles had roofs and some did not. Adding a roof did not substantially reduce the blast environment at large-scaled distances. The greatest benefit from the roof was in the area close to the cubicle where the roof dramatically reduced the blast environment behind the backwall.

Criteria is proposed for design loading in and around fully and partially vented cubicles.

CONTENTS

page

LIST OF ILLUSTRATIONS

page

page

LIST OF TABLES

INTRODUCTION

The U.S. Army Armament Command (ARMCOM) is modernizing its ammunition facilities, including equipment and protective structures used in the manufacture, processing, and storage of conventional munitions. Consistent with new safety regulations, those structures that prevent explosion propagation, damage to material, or injury to personnel are being designed to comply with criteria and methods set forth in the manual, "Structures to Resist the Effect of Accidental Explosions," (Army TM5-1300, NAVFAC P-397, and Air Force AFM-88-22) [1]. Reference 1 contains methods and criteria to determine the output from an explosion and its effects on the environment in terms of blast and fragments.

In the use of Reference 1 for the plant modernization program, it was found that certain information was either not available or quite conservative, while other information required extensive extrapolation of test data. One such deficiency is the lack of definitive information in Chapter 4 on the blast environment from partially confined explosions.

An explosion in a cubicle constitutes a partially confined explosion and is generally classified as either a fully vented or partially vented explosion. Distinction between full and partial venting depends on the duration of gas pressures built up inside the cubicle compared to the average duration of shock pressures on the cubicle walls. If the gas duration substantially exceeds the shock duration, the partially confined explosion is classified as a partially vented explosion.

The pressure, duration, and impulse of loads inside and outside the cubicle depend on several parameters, including the cubicle size and shape, charge location, composition, geometry, and size, and the area and location of openings and frangible surfaces to vent pressures from the cubicle. These parameters take on a wide range of values in practice, and, as pointed out in paragraphs 4-9 through 4-11 of Reference 1, the influence of these parameters on blast environment is essentially unknown. For partially vented explosions in cubicles, no information exists on the pressure, duration, or impulse outside the cubicle, the duration of gas pressures inside the cubicle, and the peak gas pressure inside the cubicle for explosives other than TNT. For fully vented explosions in cubicles, no information exists on the impulse and duration of pressures outside the cubicle. Some information exists on peak pressures outside the cubicle, but the information is based on a very limited number of full-scale cubicle tests involving one cubicle configuration and a very limited range of charge weights [2].

Recognizing the lack of information on partially confined explosions, Picatinny Arsenal (Manufacturing Technology Directorate) sponsored experiments at the Civil Engineering Laboratory (CEL) to develop methods and criteria for predicting the blast environment in and around cubicles. A range of charge weights was exploded inside several small-scale cubicles representing various sizes, shapes, and vent areas. Pressures generated by the explosion were recorded to establish the positive and negative pressure, duration, and impulse outside fully and partially vented cubicles and the peak gas pressure and duration inside partially vented cubicles. Ammann and Whitney, Consulting Structural Engineers, New York, under contract to Picatinny Arsenal, provided technical guidance throughout the study.

The study required a large number of tests to assure statistical accuracy of the data and to evaluate each parameter over a practical range of values. Because of the prohibitive cost of full-scale structures and the relative ease of testing small models, it was decided to employ small-scale cubicles. The results from small-scale cubicles can be extrapolated to predict results from larger cubicles since evidence is very strong that shock wave properties scale. Naturally no model experiment is a complete substitute for a full-scale test.

OBJECTIVE

The study objective was to establish the blast environment in and around fully and partially vented cubicles and to formulate methods and criteria for predicting the blast environment for practical variations in critical parameters, including the size, shape, and vent area of the cubicle and the charge weight inside the cubicle.

DESIGN OF THE EXPERIMENT

Cylindrical charges of composition B explosive were detonated inside several scaled models of cubicles constructed from 3-inch-thick steel plate. Pressures generated by the explosion were measured inside the cubicle and on the ground surface outside the cubicle in directions normal to the front, sidewalls, and backwall of the cubicle. Varied in the experiment were the cubicle configuration, cubicle volume V, vent area A, charge weight W, horizontal range from the charge to the pressure transducer R, and the vertical distance from the ground surface to the top of the cubicle wall or roof h. The range of test parameters are listed in Table 1.

The work was performed in two phases. In Phase I, charges were detonated inside small 4-wall cubicles with various-sized openings in the roof to study the blast environment from partially vented explosions. In Phase II, charges were detonated inside small and large 3-wall cubicles with and without a roof to study the blast environment from fully vented explosions. In both phases, pressures were measured inside the cubicle and outside the cubicle. Measurements outside the cubicle were taken out the open front and behind the backwall and sidewalls.

Charges

The charges were cast cylinders of composition B explosive with a length-to-diameter ratio of 1.0 (Figure 1). The charges were cast in long cylinders and then cut and machined to size. The weights of the charges were 0.50, 1.00, 1.50, 2.00 and 3.00 pounds ±1%.

The charge was detonated by an engineers special blasting cap (Type J2) placed in a 5/16-inch-diameter hole drilled into one end of the cylinder to middepth of the charge (Figure 2). A 0.25- by 0.25-inch cylindrical booster pellet of PBXN-5 explosive was placed in the hole below the cap to insure high-order detonation. The combined weight of the booster pellet and blasting cap was never greater than 0.56% of the total charge weight W.

The charge was oriented with the axis of the cylinder in a vertical plane and its center of gravity at the geometric center of the cubicle (Figure 3). The charge was held in position by a string saddle suspended from the roof of the small 4-wall cubicles. The charge in the 3-wall cubicles was supported on the top of a hollow cylinder constructed from "poster" paper (Figure 3).

Cubicles

Six cubicles were built and tested; shape and size are shown in Figure 4: (1) two small, cube-shaped, 4-wall cubicles, one with a partial roof and one without a roof; (2) two small, cube-shaped, 3-wall cubicles, one with and one without a roof; and (3) two large, rectangular-shaped, 3-wall cubicles, one with and one without a roof. All cubicles were constructed from 3-inch-thick mild steel plates, joined with full penetration welds. The 4-wall cubicles were designed for the study of the blast environment from partially vented explosions. The 3-wall cubicles were designed for the study of the exterior blast environment from fully vented explosions.

The cubicles are identified by a combination of letters and a number, such as S4WPR. The first letter (S = small, L = large) indicates the size of the cubicle. The next number and letter (3W = three walls, 4W = four walls) indicates the number of walls. The last letters (PR = partial roof, R = full roof, no letter = no roof) indicate the type of roof.

Cubicle S4WPR. Cubicle S4WPR was a small 4-wall box with a square hole in the roof. The box was buried with its roof flush with the ground surface (h = 0 foot). The interior length of the backwalls, L_b, and sidewalls, L_s, was 2.0 feet. The interior wall height H was 1.75 feet. A square vent hole, measuring 0.815 by 0.815 foot, was centered in the roof. The shape and size provided V = 7.00 ft^3 and A = 0.667 ft^2. A plate was bolted to the inside face of the roof to achieve still smaller vent areas for the box. By changing the plate, the vent area was reduced to 0.216 and 0.072 ft^2.

Table 1. Cubicle Dimensions and Range of Test Parameters

Cubicle Configuration[a]	Cubicle Dimensions: L_s (ft)	L_b (ft)	H (ft)	t_w (ft)	A (ft^2)	V (ft^3)	$A/V^{2/3}$ (ft^2/ft^3)	Charge W[b] (lb)	Scaled Lengths: W/V (lb/ft^3)	$H/W^{1/3}$ ($ft/lb^{1/3}$)	$L_s/W^{1/3}$ ($ft/lb^{1/3}$)	$L_b/W^{1/3}$ ($ft/lb^{1/3}$)	$AW^{1/3}/V$ ($lb^{1/3}/ft$)	$t_w/W^{1/3}$ ($ft/lb^{1/3}$)	$R/W^{1/3}$ ($ft/lb^{1/3}$) Min	$R/W^{1/3}$ ($ft/lb^{1/3}$) Max
Small 4-wall cubicle with partial roof (S4WPR)	2.00	2.00	1.75	0.25	0.667	7.00	0.182	0.50	0.071	2.20	2.52	2.52	0.075	0.31	2.52	63.0
								1.00	0.144	1.75	2.00	2.00	0.095	0.25	2.00	50.0
								2.00	0.287	1.39	1.59	1.59	0.120	0.20	1.59	39.7
	2.00	2.00	1.75	0.25	0.216	6.91	0.060	0.50	0.072	2.20	2.52	2.52	0.025	0.31	2.52	63.0
								1.00	0.145	1.75	2.00	2.00	0.031	0.25	2.00	50.0
								2.00	0.289	1.39	1.59	1.59	0.039	0.20	1.59	39.7
	2.00	2.00	1.75	0.25	0.072	6.91	0.020	0.50	0.072	2.20	2.52	2.52	0.008	0.31	2.52	63.0
								1.00	0.145	1.75	2.00	2.00	0.010	0.25	2.00	50.0
								2.00	0.289	1.39	1.59	1.59	0.013	0.20	1.59	39.7
Small 4-wall cubicle without roof (S4W)	2.00	2.00	2.00	0.25	4.00	8.00	1.00	0.50	0.063	2.52	2.52	2.52	0.397	0.31	2.52	63.0
								1.50	0.188	1.75	1.75	1.75	0.572	0.22	1.53	43.7
								3.00	0.375	1.39	1.39	1.39	0.721	0.17	1.39	34.7
Small 3-wall cubicle with roof (S3WR)	2.00	2.00	2.00	0.25	4.00	8.00	1.00	0.50	0.063	2.52	2.52	2.52	0.397	0.31	2.52	63.0
								1.00	0.125	2.00	2.00	2.00	0.500	0.25	2.00	50.0
								2.00	0.250	1.59	1.59	1.59	0.630	0.20	1.59	39.7
Large 3-wall cubicle with roof (L3WR)	3.00	5.00	3.67	0.25	18.4	55.0	1.27	0.50	0.009	4.62	3.78	6.30	0.265	0.31	2.52	63.0
								1.50	0.027	3.21	2.62	4.37	0.382	0.22	1.53	43.7
								3.00	0.055	2.54	2.08	3.47	0.482	0.17	1.39	34.7
Small 3-wall cubicle without roof (S3W)	2.00	2.00	2.00	0.25	8.00	8.00	2.00	0.50	0.063	2.52	2.52	2.52	0.794	0.31	2.52	63.0
								1.00	0.125	2.00	2.00	2.00	1.000	0.25	2.00	50.0
								2.00	0.250	1.59	1.59	1.59	1.260	0.20	1.59	39.7
Large 3-wall cubicle without roof (L3W)	3.00	5.00	3.67	0.25	33.4	55.0	2.31	0.50	0.009	4.62	3.78	6.30	0.482	0.31	2.52	63.0
								1.50	0.027	3.21	2.62	4.37	0.695	0.22	1.53	43.7
								3.00	0.055	2.54	2.08	3.47	0.875	0.17	1.39	34.7

[a]See Figure 4 for further details.

[b]Charge weight to within 0.01 pounds.

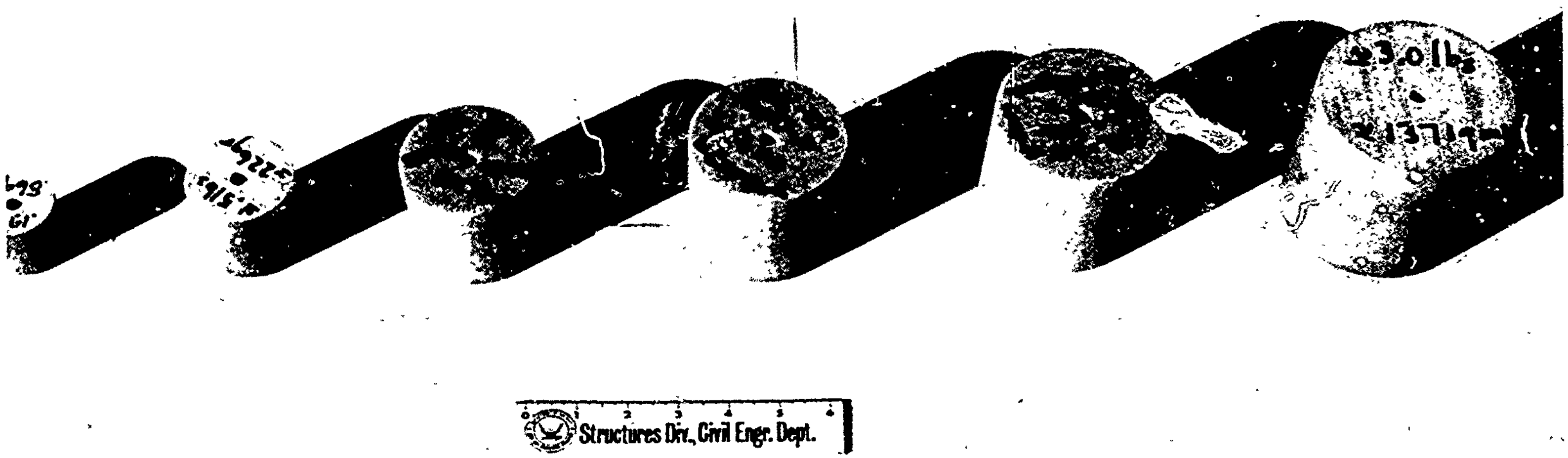


Figure 1. Test charges: cast cylinders composition B explosive.

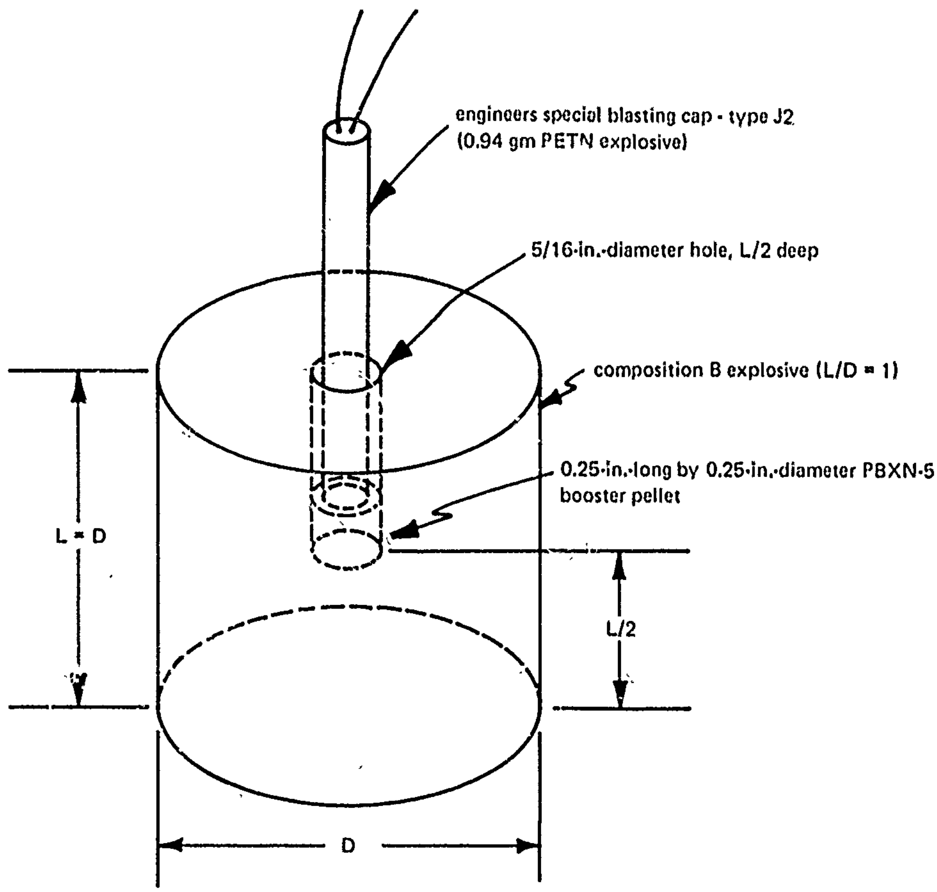


Figure 2. Charge, detonator, and booster pellet.

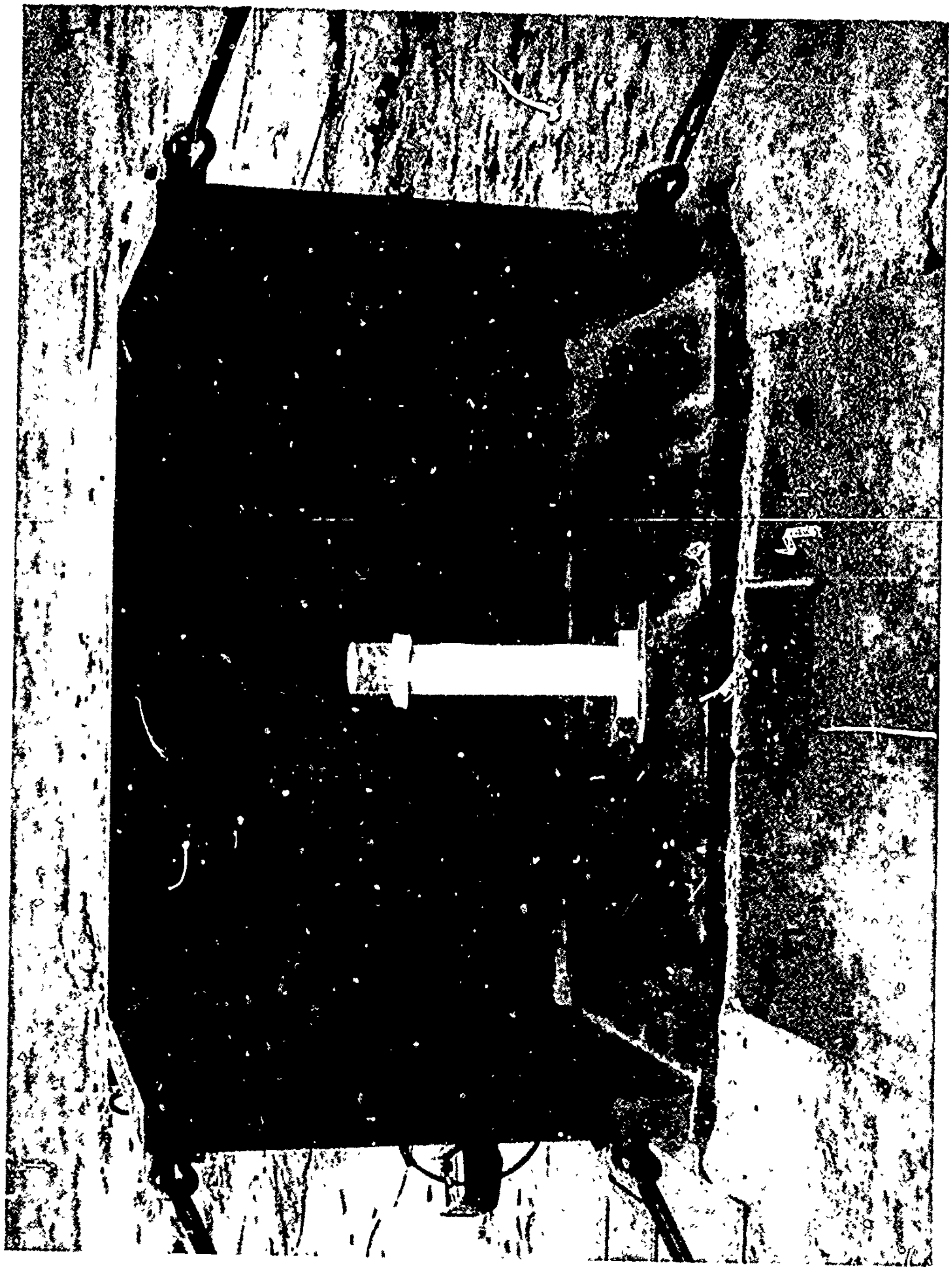
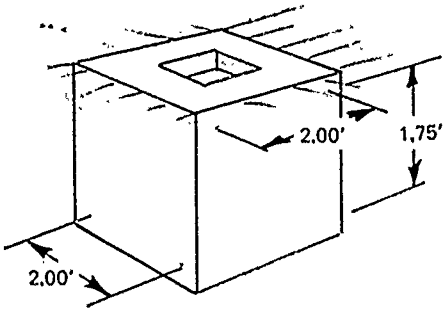
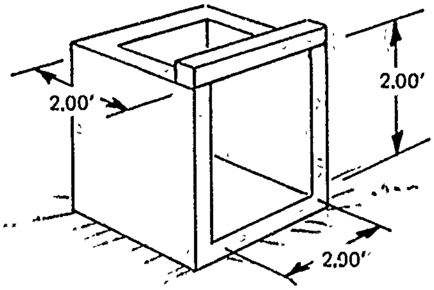


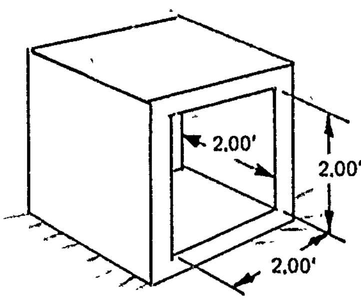
Figure 3. Typical test setup: charge at geometric center of large 3-wall cubicle on hollow paper cylinder.



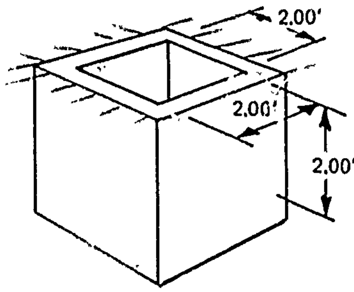
Small 4-wall cubicle with partial roof (S4WPR)



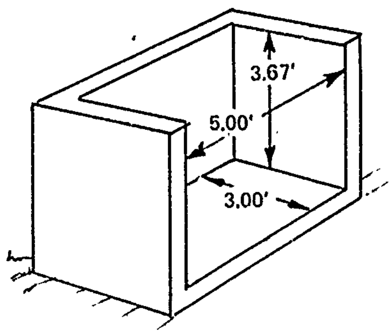
Small 3-wall cubicle without roof (S3W)



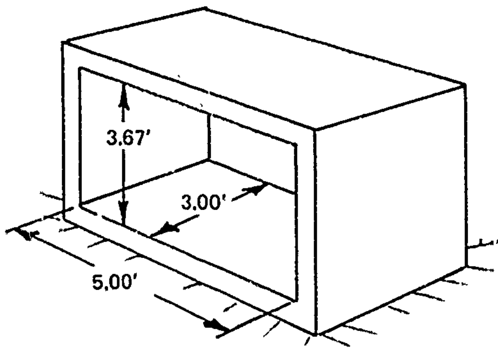
Small 3-wall cubicle with roof (S3WR)



Small 4-wall cubicle without roof (S4W)



Large 3-wall cubicle without roof (L3W)



Large 3-wall cubicle with roof (L3WR)

Note: All wall thicknesses 0.25'.

Figure 4. Shape and size of test cubicles.

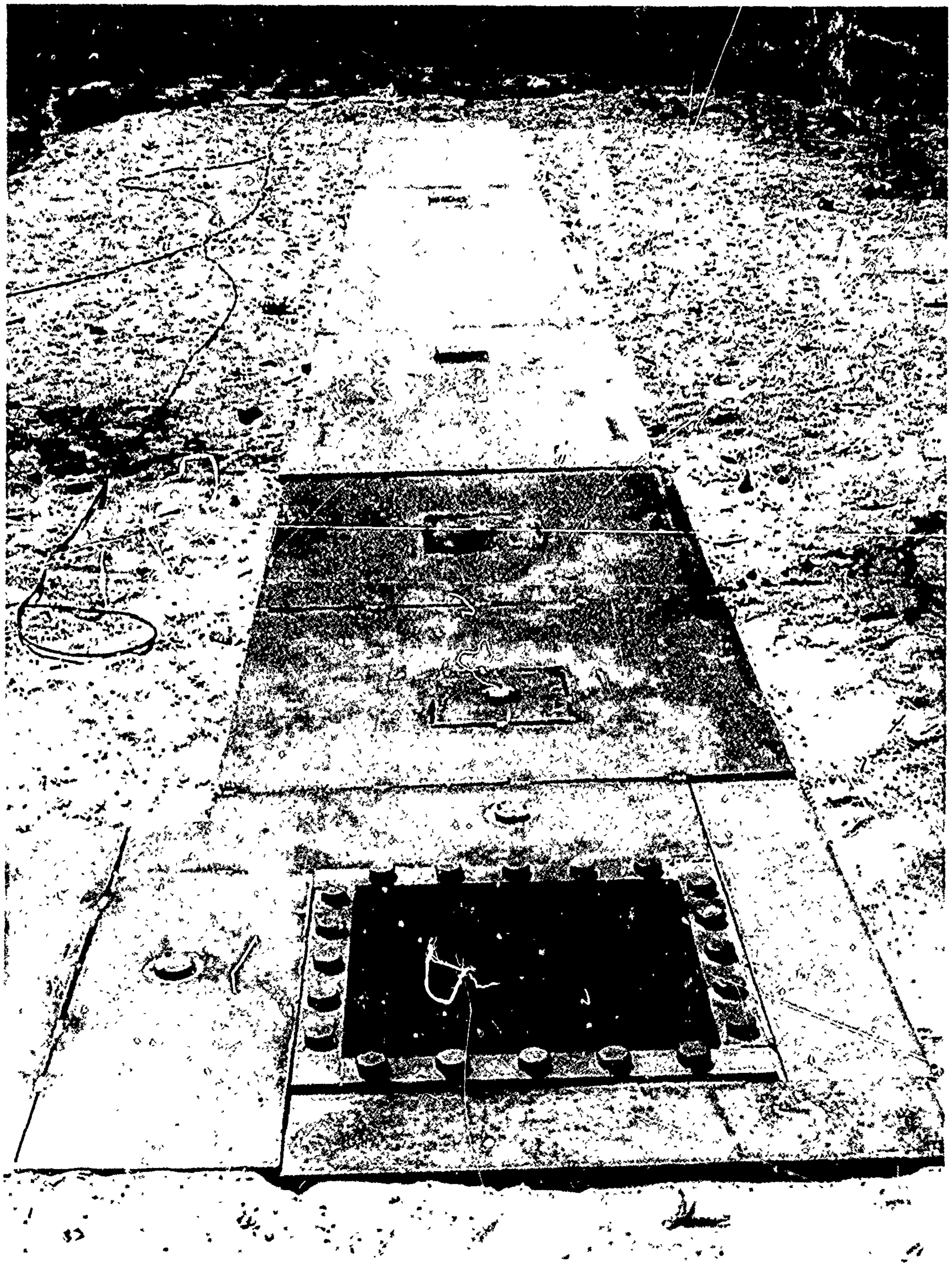


Figure 5. Small 4-wall cubicle without roof

Cubicle S4W. Cubicle S4W was a small 4-wall cube without a roof (Figure 5); $L_s = L_b = H = 2.0$ feet, $V = 8.00\ ft^3$ and $A = 4.0\ ft^2$. The box was buried with the top of the walls flush with the ground surface, thus h = 0 foot.

Cubicle S3WR. Cubicle S3WR was a small 3-wall box with a full roof; $L_s = L_b = H = 2.0$ feet, $V = 8.00\ ft^3$ and $A = 4.0\ ft^2$. The floor of the box rested on the ground surface such that h = 2.50 feet.

Cubicle L3WR. Cubicle L3WR was a large, rectangular-shaped, 3-wall box with a full roof (Figure 6); $L_s = 3.0$ feet, $L_b = 5.0$ feet, $H = 3.67$ feet, $V = 55.0\ ft^3$ and $A = 18.35\ ft^2$. The floor of the box rested on the ground surface with h = 4.17 feet.

Cubicle S3W. Cubicle S3W was a small cube-shaped, 3-wall box without a roof (Figure 7); $L_s = L_b = H = 2.0$ feet, $V = 8.00\ ft^3$, and $A = 8.00\ ft^2$. The floor of the box rested on the ground surface with h = 2.25 feet.

Cubicle L3W. Cubicle L3W was a large, rectangular-shaped, 3-wall box without a roof (Figure 3); $L_s = 3.00$ feet, $L_b = 5.00$ feet, $H = 3.67$ feet, $V = 55.0\ ft^3$, and $A = 33.35\ ft^2$. The floor of the box rested on the ground surface with h = 3.92 feet.

Instrumentation

Pressure transducers were located on lines emanating from the charge at nominal distances of 2, 4, 8, 16, 32, and 50 feet from the charge (Figure 8). The 4-wall cubicles had two gage lines, normal to adjacent walls. The 3-wall cubicles had gage lines, normal to the front, sidewalls, and backwalls. The ground surface along each gage line was leveled and covered with flat plates out to a range of 52 feet. The first 10 feet of the lines was covered with 4-foot-wide by 1/2-inch-thick steel plate. From 10 to 52 feet, the lines were covered with 3/4-inch plywood.

Transducers outside the cubicle were mounted in a steel jacket encased in 1 cubic foot of concrete. The concrete block was buried so that the gage diaphragm was flush with the ground surface (Figure 8). The pressure transducer was a Bytrex HFG piezoresistive gage, specifically designed to measure blast phenomena. The gage is supplied with an integral heat shield, consisting of a metal disk with several small holes to protect the gage diaphragm.

Pressure transducers were also located in opposite walls of the 4-wall cubicles to measure the gas pressure-time history inside the cubicle. The gage was thread-mounted at midheight of the wall so the gage diaphragm was flush with the face of the wall. The initial tests used the Bytrex HFG gage described above. Later, the Bytrex gage was replaced with a Kulite HJS piezoresistive gage which appeared to be more rugged under the severe shock and temperature environment inside the cubicle. The gage diaphragm was covered with a thin film of RTV compound to help insulate the piezoresistive sensing elements from temperature changes inside the cubicle. The gage was further protected by a perforated steel filter placed over the diaphragm. The filter protected the diaphragm from debris and attenuated the shock pressures which, in many cases, were 40 times greater than the peak gas pressure. The filter reduced the frequency response of the gage, but the reduction had an insignificant effect on the accuracy of the gas pressure data since the buildup and decay of gas pressures were relatively slow.

In the 4-wall cubicle tests, the signals from the transducers were recorded by a nominal 20-kHz recording system. The signals were passed through Endevco Model 4401 and 4470 signal conditioners, and Dana Model 3850V2 and 4472-6 amplifiers, and then were recorded on magnetic tape by a Sangamo Saber 4 tape recorder operating at 60 ips. A programmable sequence-control timer detonated the charge and operated the recording system.

The FM-signal data was digitized at 160 samples per millisecond (6.25 microseconds per sample) using an FR Model 1400 tape recorder, EMR Model 4143 proportional bandwidth discriminators, and an Electronic Engineering Company high speed digitizer. Impulse profiles were produced with a Wyle Laboratories digital spectrum analyzer. Digitized pressure and impulse data were plotted every 6.25 microseconds using an IBM 7094 computer and an SC 4020 plotter.

Peak pressures out the front of the 3-wall cubicles exceeded 100 psi. Analysis of data showed the 20-kHz recording system did not accurately measure the peak pressure at these higher pressure levels. Consequently, the 20-kHz system was replaced with a nominal 40-kHz recording system by substituting Minneapolis-Honeywell Model 104 amplifiers, increasing the tape recorder speed from 60 to 120 ips,

reducing the instrument cable length from 300 to 75 feet (by moving the instrument van closer to the cubicle), and increasing the rate at which the FM signal was digitized and plotted from 160 to 320 samples per millisecond (3.125 microseconds per sample). The 40-kHz recording system was used for pressure measurements with cubicles L3WR, S3W, and L3W.

TEST RESULTS

Computerized data plots of representative pressure-time and impulse-time histories in and around the test cubicles are displayed in Appendix A. Pertinent data from the tests are summarized in Tables 2 through 7. Table 2 describes the blast environment measured inside the 4-wall cubicles, including the peak gas pressure P_g, duration of the gas pressure t_g, and total gas impulse i_g. Unless otherwise noted, each reported data value in Table 2 is the average of 3 to 7 measurements from five identical tests. The number in parentheses represents one standard deviation. Tables 3 through 7 describe the blast environment measured outside the test cubicles. The tables list the peak positive pressure P_{so}, duration of the positive pressure t_o, total positive impulse i_s, peak negative pressure $P_{\bar{so}}$, duration of negative pressures $t_{\bar{o}}$, and the total negative impulse $i_{\bar{s}}$. Each value in Table 3 is the average of ten measurements from five identical tests; values in Tables 4 through 7 are the average of five measurements from five tests (one measurement per test).

The definition of most measurements listed in Tables 2 through 7 was standardized to facilitate reduction of data from the computerized plots. For example, durations of positive pressures t_o and t_g, were defined as the elapsed time to the point corresponding to the peak positive impulse. The peak positive pressure outside the cubicles was defined as the peak value of the pressure spike on the pressure-time curve (in some cases, particularly behind the backwall of the 3-wall cubicle, the peak value corresponded to the second pressure spike), except for plots which showed "ringing" in the gage diaphragm. In some gages, especially those at 16, 32 and 50 feet from the charge, the natural frequency of the gage diaphragm was close to the frequency of the first pressure spike. In these cases, the gage diaphragm vibrated, and the vibrations produced a false signal which oscillated about the true pressure curve. Where this occurred, a smooth exponential curve was drawn through the mean amplitude of the oscillations and extrapolated "backward" to the time of detonation. The peak positive pressure was defined as the pressure corresponding to the mean curve at time of detonation. In most cases, oscillograph traces of the pressure-time history were used to establish the peak pressure in ringing gages. The time scale on the oscillograph trace was expanded to the limits of the electronics system so that the mean pressure curve could be accurately defined.

The peak gas pressure P_g was defined as the pressure at time of detonation a smooth exponential curve drawn through the mean amplitude of the oscillations in the pressure-time plot. In most cases, the high-frequency oscillations dampened out soon enough so that most of the gas curve was well-defined. The best-fit exponential curve was accurately established from the well-defined portion of the curve and extrapolated backward to the time of detonation. Although RTV compound and a heat shield were used to isolate the gage diaphragm from thermal shock, the temperature sometimes still caused a "zero shift" in the base line, particularly in tests involving the larger charge weights. The zero shift was taken into account in establishing both P_g and i_g. The peak gas pressure was measured from a fictitious horizontal line corresponding to the pressure when the pressure trace reached a horizontal slope. For plots with a zero shift the gas impulse i_g was calculated from the equation of a best-fit, exponential curve of the re-zeroed pressure-time curve.

The Bytrex and Kulite pressure transducers were used simultaneously inside the 4-wall cubicle to measure gas pressures from the 0.5-pound charges. Both gages measured essentially the same pressure when the plots were adjusted for zero shift. Both gages had a limited life in the harsh environment, but the Kulite gages survived longer. Therefore, the Kulite gages were used exclusively in the remaining tests involving 1.0- and 2.0-pound charges.

Table 2. Gas Environment Inside Small 4-Wall Cubicle With Partial Roof

Cubicle			Charge				Gas Environment Inside Cubicle[a]				
A (ft^2)	V (ft^3)	$A/V^{2/3}$	W (lb)	W/V (lb/ft^3)	$A/W^{2/3}$ ($ft^2/lb^{2/3}$)	$AW^{1/3}/V$ ($lb^{1/3}/ft$)	P_g (psi)	t_g (msec)	$t_g/W^{1/3}$ ($msec/lb^{1/3}$)	i_g (psi-msec)	$i_g/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)
4.00[b]	8.0	1.00	0.50	0.063	6.35	0.397	c	1.59(0.05)	2.00(0.05)	c	c
			1.50	0.188	3.05	0.575	c	1.52[d]	1.33[d]	c	c
			3.00	0.375	1.92	0.721	c	2.0[d]	1.39[d]	c	c
0.667	7.00	0.182	0.50	0.072	1.06	0.075	224(13)	16.5(1.1)	20.8(1.4)	1130(110)	1424(138)
			1.00	0.145	0.667	0.095	315(39)	15.9(1.4)	15.9(1.4)	1580(290)	1580(290)
			2.00	0.287	0.420	0.120	505(52)	17.6(0.8)	14.0(0.6)	2360(550)	1870(436)
0.216	6.91	0.060	0.50	0.072	0.343	0.025	249(17)	39.4(3.0)	49.6(3.8)	3030(200)	3818(252)
			1.00	0.145	0.216	0.031	355(27)	40.9(0.7)	40.9(0.7)	3660(310)	3660(310)
			2.00	0.289	0.136	0.039	517(30)	51.3(2.0)	40.7(1.6)	5550(150)	4405(119)
0.072	6.91	0.020	0.50	0.072	0.114	0.008	226(24)	116(8)	146(11)	6790(420)	8555(529)
			1.00	0.145	0.072	0.010	329(38)	134(6)	134(6)	8800(2000)	8800(2000)
			2.00	0.289	0.045	0.013	513(21)	131(5)	104(4)	12900(1500)	10238(1190)
0.131[e]	73.2	0.0075	0.50	0.0069	[illegible]	0.0013	61(3)[f], 59(3)[g]	488(11)[f], 500[g]	610	c	–
			1.00	0.0138	0.131	0.0014	103(4)	500	500	–	–
0.267[e]	73.2	0.0153	0.50	0.0069	0.424	0.0028	57(2)	280(10)	332(10)	–	–
3.14[e]	73.2	0.179	0.50	0.0069	4.98	0.0341	46(3)	28(2)	40(2)	–	–
18.35[e,b]	116.	0.771	0.19	0.0016	55.5	0.0908	c	6.4(0.8)	11.1(1.4)		
			0.50	0.0043	29.1	0.1254	c	6.0(0.5)	7.6(0.6)		
			0.93	0.0080	19.3	0.1542	c	5.4(0.6)	5.5(0.6)		
			2.00	0.0172	11.6	0.200	c	4.7(0.6)	3.7(0.5)		
			3.00	0.0259	8.82	0.228	c	4.7(0.2)	3.3(0.1)		
33.4[h]	55.0	2.31	1.00	0.0182	33.4	0.607	c	1.02(0.18)	1.02(0.18)		
			3.00	0.0545	16.1	0.875	c	1.11(0.11)	0.77(0.08)		

[a] Average for 3 to 7 measurements; number in parentheses is one standard deviation; some listed values of t_g are really multiple shock durations.

[b] Open top box.

[c] Duration too short to accurately distinguish between gas and shock pulse.

[d] One measurement.

[e] Experimental data average for 15 or more measurements from Reference 6, based on explosions in 4-wall cubicle (L_s = 5.00 ft, L_b = 3.67 ft, H = 4.00 ft) with circular hole in roof; with no roof H = 6 ft.

[f] For 4.9-inch-diameter by 9.0-ft-long pipe stack. [g] For 4.9-inch-diameter by 4.5-ft-long pipe stack. [h] Large 3-wall cubicle without roof.

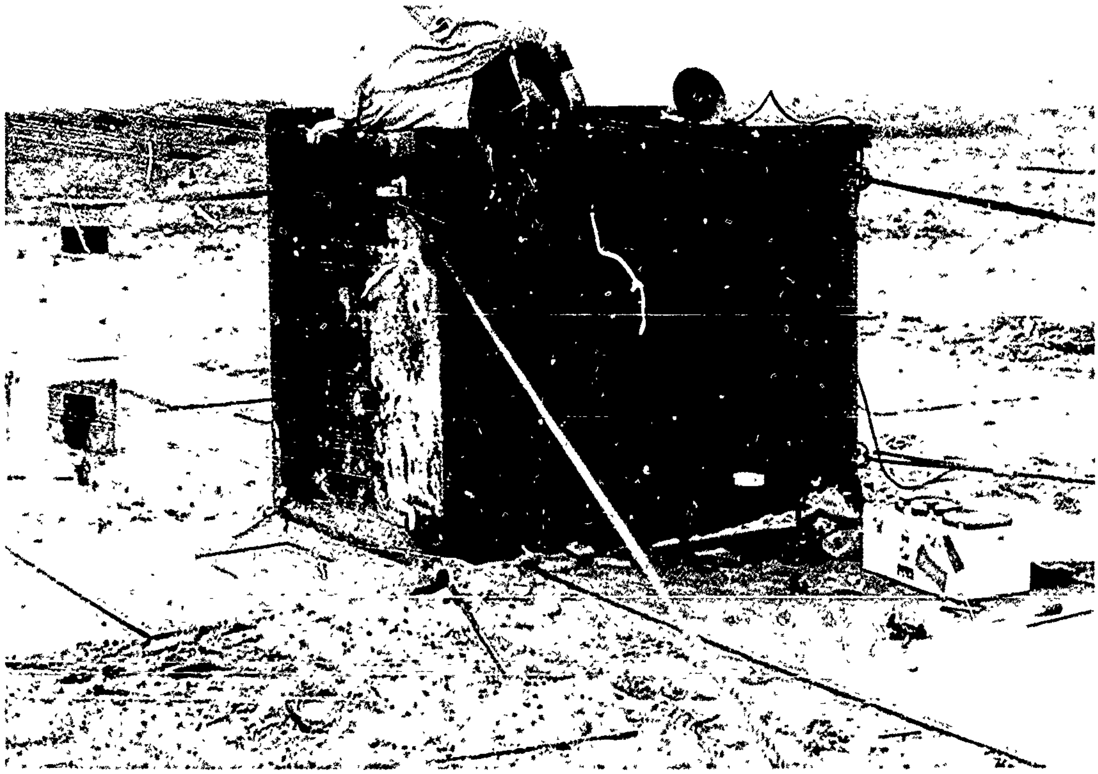


Figure 6. Large 3-wall cubicle with roof.

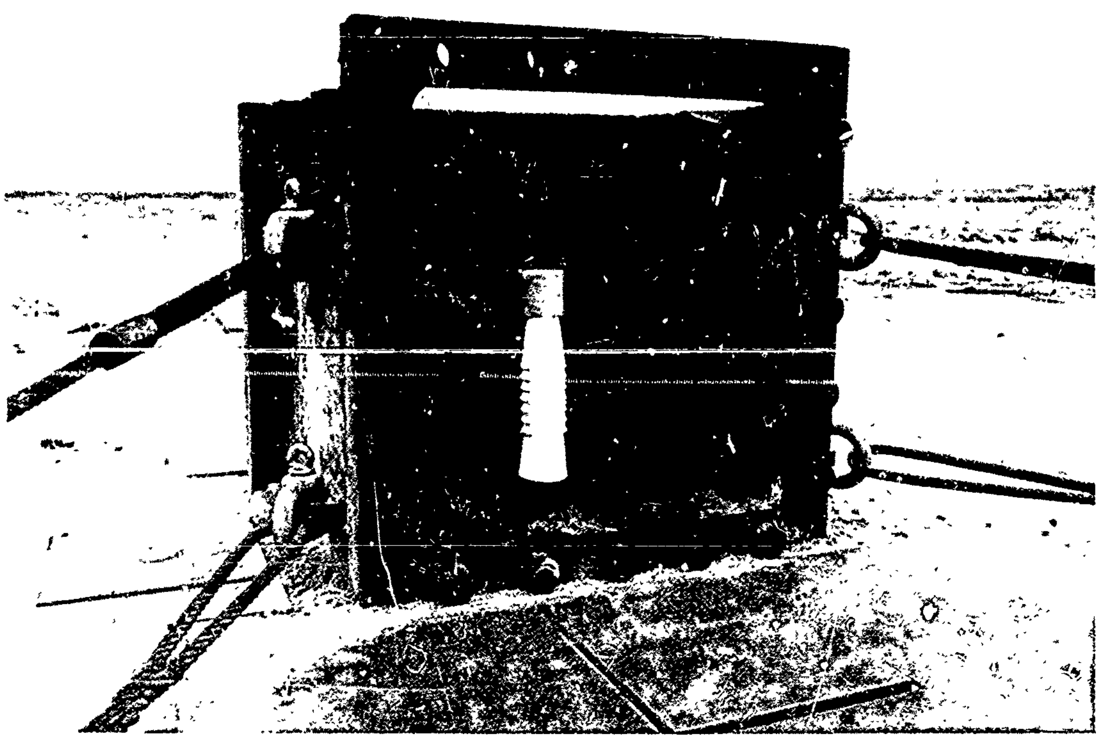


Figure 7. Small 3-wall cubicle without roof.

Table 3. Blast Environment Outside 4-Wall Cubicles With Partial Roof[a]

Cubicle			Charge			Range		Positive[b]			Negative[b]		
A (ft^2)	V (ft^3)	$A/V^{2/3}$	W (lb)	W/V (lb/ft^3)	$AW^{1/3}/V$ ($lb^{1/3}/ft$)	R (ft)	$R/W^{1/3}$ ($ft/lb^{1/3}$)	P_{so} (psi)	$t_o/W^{1/3}$ ($msec/lb^{1/3}$)	$i_s/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)	P_{so}^- (psi)	$t_o^-/W^{1/3}$ ($msec/lb^{1/3}$)	$i_s^-/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)
4.00	8.00	1.00	0.50	0.063	0.397	2.00	2.52	79 (18)	0.79(0.19)	*c*			
						4.00	5.04	28.4 (4.7)	1.25(0.18)	14.9 (2.3)			
						8.00	10.1	10.8 (0.9)	2.99(0.58)	9.75(2.02)			
						16.0	20.2	3.20(0.21)	4.42(0.84)	4.97(0.67)			
						32.0	40.3	1.06(0.09)	5.96(0.40)	2.52(0.24)			
						50.0	63.0	0.51(0.07)	6.19(0.25)	1.66(0.27)			
4.00	8.00	1.00	1.50	0.188	0.572	2.00	1.75	117 (23)	*c*	*c*			
						4.00	3.49	39.5 (4.2)	0.95(0.10)	13.9 (1.2)			
						8.00	6.99	18.1 (0.9)	1.76(0.16)	10.5 (0.9)			
						16.0	14.0	5.29(0.32)	3.41(0.68)	6.70(0.58)		*c*	
						32.0	28.0	1.97(0.13)	4.52(0.16)	3.36(0.27)			
						50.0	43.7	0.87(0.04)	4.96(0.14)	1.97(0.18)			
4.00	8.00	1.00	3.00	0.375	0.721	2.00	1.39	215 (78)	*c*	*c*			
						4.00	2.77	44.7 (0.9)	0.8 (0.05)	15.1 (3.3)			
						8.00	5.55	29.7 (7.4)	1.39(0.05)	14.1 (2.5)			
						16.0	11.1	9.05(1.1)	2.45(0.08)	7.75(0.62)			
						32.0	22.2	2.3 (0.3)	4.23(0.1)	3.61(0.54)			
						50.0	34.7	1.18(0.04)	4.69(0.17)	2.70(0.25)			
0.667	7.00	0.182	0.50	0.071	0.075	2.00	2.52	31.8 (3.4)	0.91(0.1)	7.77(0.18)	*c*	*c*	*c*
						4.00	5.04	11.0 (2.8)	1.13(0.06)	*c*	*c*	12.5(3.4)	*c*
						8.00	10.1	4.79(0.39)	4.78(0.45)	5.91(1.07)	1.2 (0.2)	13.9(3.0)	7.6 (1.8)
						16.0	20.2	2.02(0.17)	5.47(0.57)	3.52(0.29)	0.6 (0.1)	14.3(1.2)	3.9 (0.4)
						32.0	40.3	0.61(0.09)	5.68(0.38)	1.71(0.11)	0.25(0.04)	17.4(2.3)	1.8 (0.3)
						50.0	63.0	0.32(0.04)	6.36(0.39)	1.06(0.16)	0.14(0.01)	20.8(3.2)	1.0 (0.2)
0.667	7.00	0.182	1.00	0.144	0.095	2.00	2.0	42.1 (2.6)	0.74(0.09)	8.67(0.51)	*c*	*c*	*c*
						4.00	4.0	14.5 (2.3)	1.08(0.16)	8.75(1.68)	2.4 (0.4)	13.4(1.1)	10.7 (2.3)
						8.00	8.0	6.85(0.53)	1.4 (0.31)	6.45(0.98)	1.4 (0.2)	13.3(1.6)	7.1 (1.1)
						16.0	16.0	2.93(0.2)	4.62(0.53)	4.27(0.50)	0.7 (0.1)	16.4(3.4)	4.3 (0.5)
						32.0	32.0	0.86(0.09)	5.32(0.55)	2.0 (0.26)	0.30(0.03)	18.7(3.0)	2.1 (0.3)
						50.0	50.0	0.42(0.06)	5.93(0.5)	1.25(0.07)	0.17(0.02)	20.3(2.6)	1.3 (0.2)
0.667	7.00	0.182	2.00	0.287	0.120	2.00	1.59	47.6 (7.4)	0.56(0.05)	8.52(0.62)	*c*	16.6(5.5)	*c*
						4.00	3.17	19.2 (1.9)	0.91(0.04)	7.21(0.56)	2.5 (0.2)	13.0(1.2)	10.6 (1.1)
						8.00	6.35	10.1 (0.7)	1.70(0.12)	6.43(0.80)	1.7 (0.3)	13.0(1.9)	9.4 (2.4)
						16.0	12.7	3.70(0.38)	4.17(0.59)	4.4 (0.29)	0.7 (0.1)	16.8(2.3)	4.8 (0.6)
						32.0	25.4	1.24(0.1)	4.74(0.68)	2.46(0.21)	0.39(0.06)	17.7(3.8)	2.6 (0.9)
						50.0	39.7	0.65(0.1)	4.90(0.55)	1.5 (0.17)	0.19(0.03)	18.3(2.0)	1.5 (0.1)
0.216	6.91	0.060	0.50	0.071	0.025	2.00	2.52	28.4 (5.7)	0.91(0.14)	6.95(0.41)	*c*	*c*	*c*

						[illegible]	[illegible]	14.5(2.3)	[illegible]	8.75(1.68)	2.4 (0.4)	13.4(1.1)	10.7 (2.3)
						8.00	8.0	6.85(0.53)	1.4 (0.31)	6.45(0.98)	1.4 (0.2)	13.3(1.6)	7.1 (1.1)
						16.0	16.0	2.93(0.2)	4.62(0.53)	4.27(0.50)	0.7 (0.1)	16.4(3.4)	4.3 (0.5)
						32.0	32.0	0.86(0.09)	5.32(0.55)	2.0 (0.26)	0.30(0.03)	18.7(3.0)	2.1 (0.3)
						50.0	50.0	0.42(0.06)	5.93(0.5)	1.25(0.07)	0.17(0.02)	20.3(2.6)	1.3 (0.2)
0.667	7.00	0.182	2.00	0.287	0.120	2.00	1.59	47.6 (7.4)	0.56(0.05)	8.52(0.62)	*c*	16.6(5.5)	*c*
						4.00	3.17	19.2 (1.9)	0.91(0.04)	7.21(0.56)	2.5 (0.2)	13.0(1.2)	10.6 (1.1)
						8.00	6.35	10.1 (0.7)	1.70(0.12)	6.43(0.80)	1.7 (0.3)	13.0(1.9)	9.4 (2.4)
						16.0	12.7	3.70(0.38)	4.17(0.59)	4.4 (0.29)	0.7 (0.1)	16.8(2.3)	4.8 (0.6)
						32.0	25.4	1.24(0.1)	4.74(0.68)	2.46(0.21)	0.39(0.06)	17.7(3.8)	2.6 (0.9)
						50.0	39.7	0.65(0.1)	4.90(0.65)	1.5 (0.17)	0.19(0.03)	18.3(2.0)	1.5 (0.1)
0.216	6.91	0.060	0.50	0.071	0.025	2.00	2.52	28.4 (5.7)	0.91(0.14)	6.95(0.41)	*c*	*c*	*c*
						4.00	5.04	9.76(2.44)	1.3 (0.06)	5.17(0.79)	*c*	10 (0.3)	5.5 (1.0)
						8.00	10.1	3.60(0.48)	4.80(0.72)	3.36(1.05)	0.75(0.32)	11.6(2.2)	3.4 (0.7)
						16.0	20.2	1.44(0.14)	5.61(0.34)	2.11(0.35)	0.36(0.11)	13.7(3.1)	1.7 (0.5)
						32.0	40.3	0.37(0.03)	6.01(0.47)	0.94(0.11)	0.15(0.03)	13.4(1.6)	0.7 (0.1)
						50.0	63.0	0.16(0.02)	6.65(0.44)	0.59(0.09)	0.07(0.02)	19.9(4.1)	0.37(0.16)
0.216	6.91	0.060	1.00	0.144	0.031	2.00	2.0	28.7 (4.3)	0.82(0.09)	6.48(0.93)	*c*	*c*	*c*
						4.00	4.0	10.9 (2.5)	1.04(0.12)	5.01(0.76)	2.5 (0.3)	12.2(0.9)	5.0 (1.0)
						8.00	8.0	4.39(0.68)	1.2 (0.09)	3.79(0.96)	*c*	*c*	*c*
						16.0	16.0	1.9 (0.17)	4.43(0.48)	2.37(0.21)	0.45(0.1)	12.8(0.2)	*c*
						32.0	32.0	0.55(0.04)	4.82(0.43)	1.13(0.05)	0.20(0.02)	*c*	*c*
						50.0	50.0	0.25(0.04)	5.13(0.36)	0.66(0.07)	0.09(0.02)	23.3(4.2)	5.4 (0.9)
0.216	6.91	0.060	2.00	0.287	0.039	2.00	1.59	37.2 (6.9)	0.6 (0.05)	6.59(0.34)	*c*	*c*	*c*
						4.00	3.17	14.4 (2.2)	0.83(0.06)	5.21(0.57)	3.0 (0.5)	15.1(1.8)	7.6 (0.6)
						8.00	6.35	7.47(1.01)	1.15(0.06)	3.82(0.36)	1.2 (0.2)	14.0(2.9)	4.0 (0.1)
						16.0	12.7	2.72(0.34)	2.27(0.25)	2.29(0.27)	0.5 (0.1)	18.0(3.8)	2.9 (0.4)
						32.0	25.4	0.84(0.09)	4.34(0.41)	1.31(0.1)	0.2 (0.05)	16.9(2.0)	1.2 (0.1)
						50.0	39.7	0.39(0.06)	4.52(0.44)	0.8 (0.09)	0.11(0.02)	18.7(1.3)	0.9 (0.2)
0.072	6.91	0.020	0.50	0.071	0.008	2.00	2.52	20.5 (4.7)	0.86(0.1)	3.29(0.64)	*c*	*c*	*c*
						4.00	5.04	3.75(0.66)	1.08(0.05)	2.16(0.28)	*c*	16.0(3.0)	2.7 (0.6)
						8.00	10.1	1.58(0.29)	1.22(0.1)	1.31(0.18)	*c*	13.2(1.9)	1.3 (0.1)
						16.0	20.2	0.65(0.08)	2.02(0.21)	0.75(0.17)	*c*	*c*	*c*
						32.0	40.3	0.2 (0.01)	5.73(1.05)	0.37(0.03)	*c*	16.3(5.2)	0.26(0.05)
						50.0	63.0	0.09(0.01)	6.59(1.36)	0.23(0.03)	*c*	*c*	*c*
0.072	6.91	0.020	1.00	0.144	0.010	2.00	2.0	19.9 (4.6)	0.72(0.09)	4.25(0.5)			
						4.00	4.0	8.04(1.0)	0.96(0.11)	2.62(0.16)			
						8.00	8.0	2.41(0.33)	1.08(0.12)	1.64(0.2)		*c*	
						16.0	16.0	1.05(0.13)	2.46(0.36)	0.95(0.18)			
						32.0	32.0	0.3 (0.04)	4.8 (0.91)	0.49(0.03)			
						50.0	50.0	0.11(0.02)	5.4 (0.61)	0.27(0.03)			
0.072	6.91	0.020	2.00	0.287	0.013	2.00	1.59	36.5 (4.5)	0.52(0.03)	5.45(0.66)	6.5 (0.5)	*c*	11.0 (2.7)
						4.00	3.17	11.0 (1.8)	0.82(0.07)	3.44(0.25)	2.6 (0.3)	11.6(0.4)	4.2 (1.1)
						8.00	6.35	4.35(0.65)	0.98(0.13)	2.18(0.24)			
						16.0	12.7	1.74(0.16)	1.65(0.29)	1.12(0.11)		*c*	
						32.0	25.4	0.51(0.06)	3.45(0.74)	0.63(0.05)			
						50.0	39.7	0.22(0.04)	4.0 (0.85)	0.38(0.05)			

[a]Details of cubicle in Table 1 and Figure 4.

[b]Average of 10 measurements; number in parentheses is one standard deviation.

[c]Value not well defined.

2

Table 4. Blast Environment Outside Small 3-Wall Cubicle Without Roof[a]

Charge, W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Positive Pressure,[b] P_{so} (psi)			Positive Duration[b] $t_o/W^{1/3}$ ($msec/lb^{1/3}$)			Positive Impuls $i_s/W^{1/3}$ (psi-msec/	
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side
0.50	2.58	2.65	2.71	250[c]	13.7 (1.5)	16.2 (0.9)	0.45(0.13)	2.60(0.06)	1.85(0.06)	35.5 (4.0)	13.9 (0.4
	5.08	5.15	5.18	110 (7)	18.6 (2.3)	16.4 (0.5)	1.3 (0.1)	2.4 (0.3)	1.6 (0.1)	29.5 (4.7)	13.0 (1.8
	9.99	10.1	10.2	16.9 (1.9)	12.9 (1.4)	8.99(0.1)	2.2 (0.1)	1.9 (0.6)	2.3 (0.4)	14.9 ([illegible])	7.3 (1.6
	20.1	20.2	20.3	5.05(0.19)	3.84(0.19)	3.58(0.29)	3.82(0.06)	3.8 (0.1)	2.7 (0.2)	7.16(0.24)	4.72(0.11
	40.3	40.4	40.5	1.53(0.04)	1.42(0.08)	0.93(0.06)	4.23(0.05)	4.6 (0.2)	2.94(0.03)	3.39(0.09)	2.78(0.03
	62.9	63.1	63.2	1.01(0.04)	0.81(0.08)	0.53(0.04)	5.00(0.1)	5.3 (0.2)	3.1 (0.1)	2.19(0.05)	1.75(0.10
1.00	2.03	2.11	2.15	441 (34)	24.1 (1.9)	15.9 (2.2)	0.62(0.29)	2.22(0.06)	1.1 (0.1)	46 (6)	13.9 (0.9
	4.06	4.07	4.15	195 (17)	24.1 (0.8)	23.7 (1.2)	0.58(0.31)	2.1 (0.4)	1.82(0.03)	21.3 (2.0)	13.2[c]
	7.93	8.01	8.06	28.2 (1.2)	16.9 (1.0)	9.74(0.60)	1.8 (0.1)	1.26(0.05)	2.08(0.04)	19.1 (0.6)	6.85(0.24
	16.0	16.0	16.1	7.62(0.19)	5.09(0.25)	4.28(0.11)	3.1 (0.2)	3.1 (0.3)	2.18(0.02)	8.17(0.29)	5.53(0.19
	32.0	32.1	32.1	2.07(0.05)	1.90(0.06)	1.32(0.11)	3.9 (0.1)	3.9 (0.1)	2.43(0.04)	3.84(0.03)	3.24(0.05
	49.9	50.1	50.2	1.28(0.05)	0.99(0.02)	0.71(0.03)	4.9 (0.1)	4.8 (0.3)	2.58(0.02)	2.54(0.03)	1.99(0.02
2.00	1.62	1.71	1.71	743 (49)	33.0 (4.4)	22.0 (2.0)	0.5 (0.2)	1.7 (0.2))	0.89(0.02)	55 (7)	12.9 (0.4
	3.23	3.27	[illegible]	311 (42)	37.3 (2.1)	34.9 (0.5)	0.6 (0.4)	1.8 (0.3)	1.04(0.02)	31.8 (1.7)	13.0 (1.3
	6.30	6.40	[illegible]	45.9 (0.8)	22.5 (1.3)	12.6 (0.6)	1.6 (0.1)	1.09(0.05)	1.76(0.04)	24.9 (1.3)	7.13(0.31
	12.7	12.8	12.8	12.6 (0.6)	6.47(0.10)	6.21(0.17)	2.3 (0.1)	2.5 (0.1)	2.0 (0.1)	10.1 (0.1)	6.05(0.08
	25.4	25.5	25.5	3.12(0.08)	2.39(0.07)	1.86(0.06)	3.4 (0.1)	3.3 (0.1)	2.1 (0.1)	4.37(0.12)	3.69(0.09
	39.6	39.8	39.8	1.61(0.04)	1.39(0.06)	1.06(0.09)	4.5 (0.1)	4.4 (0.2)	2.3 (0.2)	2.99(0.15)	2.41(0.11

Charge, W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Negative Pressure,[b] P_{so}^- (psi)			Negative Duration[b] $t_o^-/W^{1/3}$ ($msec/lb^{1/3}$)			Negative Impuls $i_s^-/W^{1/3}$ (psi-msec/	
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side
0.50	2.58	2.65	2.71	*d*	4.0 (0.6)	2.7 (0.1)	*d*	*e*	4.8 (0.9)	*d*	*e*
	5.08	5.15	5.18	*d*	4.1 (0.4)	5.0 (0.4)	*d*	3.9 (1.2)	3.7 (0.3)	*d*	8.5 (2.2
	9.99	10.1	10.2	2.8 (0.3)	1.8 (0.2)	1.6 (0.1)	9.9 (2.4)	8.5 (4.3)	6.5 (1.1))	10.6 (1.9)	6.3 (2.5
	20.1	20.2	20.3	1.1 (0.1)	1.0 (0.1)	0.8 (0.1)	10.6(1.5)	11.7(0.3)	8.3 (0.7)	5.6 (0.6)	4.3 (0.2
	40.3	40.4	40.5	0.63(0.03)	0.52(0.02)	0.47(0.05)	11.0(1.4)	11.9(0.3)	7.0 (2.3)	3.9 (0.1)	2.5 (0.1
	62.9	63.1	63.2	0.30(0.03)	0.31(0.02)	0.27(0.01)	16.4(0.1)	12.6(0.7)	4.9 (0.1)	1.9 (0.3)	1.53(0.15
1.00	2.03	2.11	2.15	*d*	4.5 (1.4)	2.8 (0.2)	*d*	*e*	4.2 (1.4)	*d*	*e*
	4.06	4.07	4.15	*d*	4.3 (0.7)	4.4 (0.4)	*d*	*e*	2.78(0.05)	*d*	*e*
	7.93	8.01	8.06	4.7 (0.5)	2.3 (0.2)	1.8 (0.4)	10.0(1.6)	5.9(0.2)	7.0 (0.4)	13.6 (3.1)	4.6 (0.4
	16.0	16.0	16.1	1.6 (0.2)	1.0 (0.2)	0.9 (0.2)	14.0(0.7)	10.1(0.2)	6.8 (0.6)	7.52(0.05)	4.8 (0.2
	32.0	32.1	32.1	0.77(0.05)	0.5 (0.1)	0.52(0.02)	10.4(0.6)	12.1(1.0)	5.3 (0.7)	4.1 (0.1)	3.2 (0.3
	49.9	50.1	50.2	0.34(0.08)	0.32(0.01)	0.34(0.06)	13.0(0.7)	10.9(0.3)	6.0 (2.8)	1.9 (0.4)	1.66(0.06
2.00	1.62	1.71	1.71	*d*	4.2 (0.4)	3.1 (0.3)	*d*	*e*	4.1 (1.1)	*d*	*e*
	3.23	3.27	3.29	*d*	4.4 (0.9)	3.7 (0.6)	*d*	*e*	2.6 (0.4)	*d*	*e*
	6.30	6.40	6.40	5.8 (0.8)	2.6 (0.2)	1.7 (0.2)	9.6(2.5)	5.0(0.2)	2.9 (0.3)	15.3 (3.2)	4.6 (0.3
	12.7	12.8	12.8	2.0 (0.2)	1.3 (0.1)	1.0 (0.2)	11.3(0.4)	11.7(1.7)	2.4 (0.2)	8.4 (1.1)	5.2 (0.2
	25.4	25.5	25.5	0.88(0.06)	0.64(0.06)	0.51(0.01)	8.1(1.0)	16.7(3.2)	3.0 (1.3)	4.0 (0.2)	2.8[f]
	39.6	39.8	39.8	0.42(0.05)	0.41(0.03)	0.31(0.02)	9.5(0.6)	13.0(2.8)	4.7 (0.4)	2.2 (0.3)	2.2[f]

[a]Details of cubicle in Table 1 and Figure 4.

[b]Average of 5 measurements; number in parentheses is one standard deviation.

[c]One measurement.

[d]Pressure too low to accurately resolve from pressure-time plot.

[e]Duration exceeds range of digitized data.

[f]Extrapolation of impulse curve.

nvironment Outside Small 3-Wall Cubicle Without Roof[a]

b	Positive Duration[b] $t_o/W^{1/3}$ (msec/lb$^{1/3}$)			Positive Impulse[b] $i_s/W^{1/3}$ (psi-msec/lb$^{1/3}$)		
Back	Front	Side	Back	Front	Side	Back
16.2 (0.9)	0.45(0.13)	2.60(0.06)	1.85(0.06)	35.5 (4.0)	13.9 (0.4)	5.34(0.43)
16.4 (0.5)	1.3 (0.1)	2.4 (0.3)	1.6 (0.1)	29.5 (4.7)	13.0 (1.8)	7.48(0.35)
8.99(0.1)	2.2 (0.1)	1.9 (0.6)	2.3 (0.4)	14.9 (0.5)	7.3 (1.6)	3.46(0.14)
3.58(0.29)	3.82(0.06)	3.8 (0.1)	2.7 (0.2)	7.16(0.24)	4.72(0.11)	2.06(0.09)
0.9[illegible](0.06)	4.23(0.05)	4.6 (0.2)	2.94(0.03)	3.39(0.09)	2.78(0.03)	1.36(0.10)
0.53(0.04)	5.00(0.1)	5.3 (0.2)	3.1 (0.1)	2.19(0.05)	1.75(0.10)	0.73(0.02)
15.9 (2.2)	0.62(0.29)	2.22(0.06)	1.1 (0.1)	46 (6)	13.9 (0.9)	5.4[c]
23.7 (1.2)	0.58(0.31)	2.1 (0.4)	1.82(0.03)	21.3 (2.0)	13.2[c]	8.33(0.32)
9.74(0.60)	1.8 (0.1)	1.26(0.05)	2.08(0.04)	19.1 (0.6)	6.85(0.24)	4.11(0.07)
4.28(0.11)	3.1 (0.2)	3.1 (0.3)	2.18(0.02)	8.17(0.29)	5.53(0.19)	2.57(0.12)
1.32(0.11)	3.9 (0.1)	3.9 (0.1)	2.43(0.04)	3.84(0.03)	3.24(0.05)	1.46(0.06)
0.71(0.03)	4.9 (0.1)	4.8 (0.3)	2.58(0.02)	2.54(0.05)	1.99(0.02)	0.89(0.02)
22.0 (2.0)	0.5 (0.2)	1.7 (0.2))	0.[illegible]9(0.02)	55 (7)	12.9 (0.4)	5.09(0.50)
34.9 (0.5)	0.6 (0.4)	1.8 (0.3)	1.04(0.02)	31.8 (1.7)	13.0 (1.3)	7.91(0.15)
12.6 (0.6)	1.6 (0.1)	1.09(0.05)	1.78(0.04)	24.9 (1.3)	7.13(0.31)	4.09(0.10)
6.21(0.17)	2.3 (0.1)	2.5 (0.1)	2.0 (0.1)	10.1 (0.1)	6.05(0.08)	2.78(0.13)
1.86(0.06)	3.4 (0.1)	3.3 (0.1)	2.1 (0.1)	4.37(0.12)	3.69(0.09)	1.61(0.06)
1.06(0.09)	4.5 (0.1)	4.4 (0.2)	2.3 (0.2)	[illegible].99(0.15)	2.41(0.11)	1.03(0.04)

b	Negative Duration[b] $t_o^-/W^{1/3}$ (msec/lb$^{1/3}$)			Negative Impulse[b] $i_s^-/W^{1/3}$ (psi-msec/lb$^{1/3}$)		
Back	Front	Side	Back	Front	Side	Back
2.7 (0.1)	*d*	*e*	4.8 (0.9)	*d*	*e*	6.0 (0.4)
5.0 (0.4)	*d*	3.9 (1.2)	3.7 (0.3)	*d*	8.5 (2.2)	8.3 (1.5)
1.6 (0.1)	9.9 (2.4)	8.5 (4.3)	6.5 (1.1)	10.6 (1.9)	6.3 (2.5)	3.5 (0.5)
0.8 (0.1)	10.6(1.5)	11.7(0.3)	8.3 (0.7)	5.6 (0.6)	4.3 (0.2)	2.0 (0.1)
0.47(0.05)	11.0(1.4)	11.9(0.3)	7.0 (2.3)	3.9 (0.1)	2.5 (0.1)	1.1 (0.1)
0.27(0.01)	16.4(0.1)	12.6(0.7)	4.9 (0.1)	1.9 (0.3)	1.53(0.15)	0.61(0.02)
2.8 (0.2)	*d*	*e*	4.2 (1.4)	*d*	*e*	5.2 (1.0)
4.4 (0.4)	*d*	*e*	2.78(0.05)	*d*	*e*	7.2 (0.3)
1.8 (0.4)	10.0(1.6)	5.9(0.2)	7.0 (0.4)	13.6 (3.1)	4.6 (0.4)	3.8 (0.9)
0.9 (0.2)	14.0(0.7)	10.1(0.2)	6.8 (0.6)	7.52(0.05)	4.8 (0.2)	2.4 (0.1)
0.52(0.02)	10.4(0.6)	12.1(1.0)	5.3 (0.7)	4.1 (0.1)	3.2 (0.3)	1.27(0.06)
0.34(0.06)	13.0(0.7)	10.9(0.3)	6.0 (2.8)	1.9 (0.4)	1.66(0.06)	0.9 (0.2)
3.1 (0.3)	*d*	*e*	4.1 (1.1)	*d*	*e*	4.2 (0.6)
3.7 (0.6)	*d*	*e*	2.6 (0.4)	*d*	*e*	3.9 (0.3)
1.7 (0.2)	9.6(2.5)	5.0(0.2)	2.9 (0.3)	15.3 (3.2)	4.6 (0.3)	4.0 (0.2)
1.0 (0.2)	11.3(0.4)	11.7(1.7)	2.4 (0.2)	8.4 (1.1)	5.2 (0.2)	2.4 (0.2)
0.51(0.01)	8.1(1.0)	16.7(3.2)	3.0 (1.3)	4.0 (0.2)	2.8[f]	1.42(0.04)
0.31(0.02)	9.5(0.6)	13.0(2.8)	4.7 (0.4)	2.2 (0.3)	2.2[f]	1.04(0.05)

rd deviation.

Table 5. Blast Environment Outside Large 3-Wall Cubicle Without Roof[a]

Charge, W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Positive Pressure[b] P_{so} (psi)			Positive Duration[b] $t_o/W^{1/3}$ ($msec/lb^{1/3}$)			Positive Impulse[b] $i_s/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.60	c	2.39	119 (13)	d	5.3	1.6 (0.2)	c	2.0[d]	37 (2)	c	6.3[d]
	5.12	5.04	5.17	45 (5)	9.80(0.65)	5.82(0.82)	2.0 (0.1)	4.6 (0.1)	7.0 (0.2)	27 (2)	11.2 (0.8)	6.6 (0.6)
	10.2	10.0	10.2	21.6 (1.5)	5.95(0.79)	5.03(0.26)	2.3 (0.2)	4.1 (0.2)	7.0 (0.2)	15.8 (0.4)	9.9 (0.1)	5.7 (0.2)
	20.2	20.1	20.2	6.38(0.29)	3.70(0.52)	2.96(0.22)	4.3 (0.2)	4.3 (0.1)	7.6 (0.1)	9.1 (0.2)	5.88(0.05)	3.9 (0.1)
	40.4	40.3	40.4	1.87(0.03)	1.27(0.05)	0.99(0.05)	4.4 (0.1)	[illegible] (0.1)	7.9 (0.1)	3.92(0.06)	3.4 (0.1)	2.28(0.03)
	63.1	63.0	63.1	0.94(0.04)	0.77(0.08)	0.57(0.02)	5.8 (0.1)	[illegible]	[illegible] (0.1)	2.57(0.01)	2.15(0.05)	1.59(0.03)
1.50	1.82	c	1.71	297 (81)	c	13.1 (3.4)	1.6 (0.2)	c	4.6 (0.3)	57 (9)	c	10.5 (1.2)
	3.55	3.49	3.56	123 (20)	18.6 (2.5)	10.7 (0.9)	1.41(0.1)	3.1 (0)	4.4 (0.2)	34 (4)	13.[illegible] (0.4)	10.5 (0.5)
	7.02	6.94	7.03	37.2 (5.5)	14.1 (2.1)	9.46(0.99)	1.89(0.04)	2.8 (0.[illegible])	4.5 (0.1)	21.7 (0.5)	11.6 (0.3)	8.9 (0.3)
	14.0	13.9	14.0	12.1 (0.4)	5.88(0.15)	5.16(0.28)	2.76(0.05)	2.3 (0.1)	5.0 (0.2)	11.2 (0.2)	7.3 (0.2)	6.1 (0.1)
	28.0	28.0	28.0	3.10(0.07)	2.50(0.10)	2.08(0.06)	3.65(0.09)	3.72(0.03)	[illegible] (0.3)	4.93(0.06)	4.31(0.06)	3.6 (0.1)
	43.7	43.7	c	1.54(0.06)	1.30(0.04)	c	4.91(0.04)	4.5 (0.1)	c	3.31(0.05)	2.74(0.04)	c
3.00	1.45	c	1.38	386 (71)	c	18.3 (4.4)	1.1 (0.1)	c	4.0 (0.1)	64 (7)	c	11.9 (0.[illegible])
	2.81	2.77	2.82	177 (31)	22.7 (4.2)	23.4 (3.4)	1.10(0.04)	2.4 (0.2)	3.8 (0.3)	[illegible] (5)	13.5 (0.6)	11.6 (0.5)
	5.56	5.50	5.56	48.4 (4.1)	20.9 (1.0)	16.1 (1.1)	1.32(0.07)	2.4 (0.1)	4.2 (0.2)	27.7 (0.8)	[illegible]2.8 (0.3)	10.3 (0.5)
	11.1	11.0	11.1	19.6 (0.5)	8.14(0.13)	6.83(0.21)	2.13(0.03)	2.37(0.04)	4.7 (0.1)	12.6 (0.[illegible])	8.[illegible] (0.3)	8.0 (0.2)
	22.2	22.1	22.2	4.31(0.09)	3.30(0.14)	2.60(0.11)	3.2 (0.1)	3.30(0.05)	4.9 (0.1)	5.9 (0.1)	4.9 (0.1)	4.50(0.03)
	34.6	34.6	34.6	2.34(0.08)	7.92(0.10)	1.23(0.18)	4.4 (0.1)	4.00(0.05)	5.5 (0.2)	3.88(0.07)	3.6 (0.3)	2.8 (0.3)

Charge, W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Negative Pressure[b] P_{so}^- (psi)			Negative Duration[b] $t_o^-/W^{1/3}$ ($msec/lb^{1/3}$)			Negative Impulse[b] $i_s^-/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.60	c	2.39	e	c	e	e	c	e	e	c	e
	5.12	5.04	5.17	e	3.6 (0.6)	2.1 (0.3)	e	10.3 (1.0)	7.3 (0.3)	e	14.6 (0.7)	8.7 (0.2)
	10.2	10.0	10.2	3.2 (0.8)	2.4 (0.2)	1.4 (0.1)	8.8 (0.8)	14.5 (0.9)	7.2 (0.3)	14.9 (2.3)	11.5 (0.2)	6.4 (0.[illegible])
	20.2	20.1	20.2	1.5 (0.1)	1.14(0.04)	0.78(0.06)	12.2 (0.6)	9.1 (2.4)	7.7 (0.2)	9.3 (0.3)	5.5 (0.5)	3.9 (0.2)
	40.4	40.3	40.4	0.89(0.03)	0.64(0.07)	0.41(0.02)	10.7 (1.0)	14.8 (2)	8.2 (0.1)	5.4 (0.1)	3.8 (0.5)	2.26(0.05)
	63.1	63.0	63.1	0.40(0.03)	0.41(0.08)	0.26(0.02)	12.0 (0.6)	13.8 (1.0)	10.8 (0.7)	2.60(0.05)	2.1 (0.1)	1.61(0.07)
1.50	1.82	c	1.71	e	c	3.4 (0.3)	e	c	6.9 (0.8)	e	c	12.0 (1.8)
	3.55	3.49	3.56	e	4.9 (0.3)	3.2 (0.1)	e	12.6 (1.4)	9.4 (2.5)	e	18.8 (2.0)	12.5 (0.4)
	7.02	6.94	7.03	3.7 (0.4)	3.1 (0.1)	2.5 (0.1)	e	13.9 (0.8)	11.6 (0.7)	e	12.7 (2.7)	10.0 (0.2)
	14.0	13.9	14.0	1.9 (0.2)	1.1 (0.1)	1.4 (0.1)	12.0 (2.3)	14.3 (0.3)	10.0 (0.4)	8.4 (0.7)	7.9 (0.2)	6.0 (0.3)
	28.0	28.0	28.0	1.21(0.06)	0.8 (0.1)	0.74(0.04)	10.0 (0.6)	14.3 (0.3)	11.5 (1.3)	5.8 (0.1)	4.5 (0.1)	3.6 (0.1)
	43.7	43.7	c	0.54(0.02)	0.45(0.04)	c	15.2 (0.1)	14.0 (0.3)	d	3.35(0.02)	2.7 (0.1)	d
3.00	1.45	c	1.38	e	c	3.1 (0.5)	e	d	7.0 (2.8)	e	d	10.8 (1.0)
	2.81	2.77	2.82	e	5.0 (0.4)	3.2 (0.2)	e	10.6 (0.7)	6.7 (1.6)	e	20 (1.2)	11.2 (0.8)
	5.56	5.50	5.56	6.3 (1.0)	3.6 (0.2)	2.7 (0.2)	e	11.1[d]	9.5 (0.3)	e	14.7[d]	11.0 (0.3)
	11.1	11.0	11.1	2.8 (0.2)	1.4 (0.2)	1.6 (0.1)	11.9 (0.2)	11.0[d]	7.4 (0.3)	11.4 (0.1)	8.8[d]	6.0 (0.3)
	22.2	22.1	22.2	1.42(0.05)	0.84(0.07)	0.97(0.03)	11.7 (0.2)	15.6 (2.2)	8.9 (0.3)	6.2 (0.1)	5.1 (0.2)	4.35(0.02)
	34.6	34.6	34.6	0.65(0.09)	0.60(0.09)	0.90(0.15)	15.4 (0.6)	12.4 (0.8)	7.6 (0.6)	3.9 (0.1)	3.8 (0.8)	4.3 (0.4)

[a] Details of cubicle in Table 1 and Figure 4.

[b] Average of 5 measurements; number in parentheses is one standard deviation.

[c] No pressure transducer at this location.

[d] One measurement.

[e] Poor resolution of data or value exceeds range of digitized data.

Table 6. Blast Environment Outside Small 3-Wall Cubicle With Roof[a]

Charge W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Positive Pressure,[b] P_{so} (psi)			Positive Duration[b] $t_o/W^{1/3}$ ($msec/lb^{1/3}$)			Positive Impulse[b] $i_s/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.36	2.68	2.68	320 (28)	15.0 (1.6)	4.85(0.41)	2.2 (0.2)	2.7 (0.1)	3.9 (0.3)	88 (6)	11.9 (0.3)	8.47(0.45)
	4.88	5.20	5.20	77 (4)	18.6 (0.8)	6.19(0.75)	3.1 (0.1)	2.3 (0.1)	3.8 (0.1)	44 (4)	10.6 (0.2)	6.82(0.39)
	9.92	10.2	10.2	35.7 (2.6)	9.77(1.27)	4.24(0.25)	2.4 (0.1)	2.4 (0.1)	3.7 (0.1)	26.3 (0.8)	6.59(0.43)	4.81(0.20)
	20.3	20.3	20.3	7.38(0.39)	3.08(0.03)	2.20(0.13)	3.7 (0.1)	3.8 (0.3)	4.0 (0.1)	10.8 (0.2)	4.00(0.11)	3.06(0.31)
	40.2	40.5	40.5	2.04(0.12)	1.11(0.04)	0.83(0.03)	4.2 (0.1)	5.3 (0.1)	4.5 (0.1)	4.08(0.06)	2.26(0.03)	1.71(0.04)
	62.8	63.2	63.2	1.12(0.02)	0.61(0.02)	0.55(0.04)	5.5 (0.1)	6.0 (0.1)	5.0 (0.2)	2.55(0.03)	1.36(0.05)	1.08(0.03)
1.00	1.88	2.13	2.13	579 (70)	18.8 (5.8)	5.45(0.37)	1.6 (0.3)	2.42(0.05)	3.43(0.05)	104 (4)	11.1 (0.6)	8.48(0.14)
	3.88	4.13	4.13	131 (5)	22.0 (2.5)	7.45(1.07)	2.8 (0.2)	2.1 (0.2)	3.20(0.07)	48 (1)	10.7 (0.5)	7.41(0.11)
	7.88	8.13	8.13	54.0 (2.9)	11.0 (1.1)	5.11(0.46)	1.99(0.02)	1.96(0.06)	3.01(0.06)	32.6 (1)	6.99(0.16)	5.31(0.05)
	15.9	16.1	16.1	11.1 (0.3)	4.01(0.22)	2.60(0.19)	3.0 (0.1)	3.0 (0.1)	3.4 (0.2)	13.6 (0.1)	4.37(0.04)	3.26(0.07)
	31.9	32.1	32.1	2.84(0.09)	1.53(0.02)	1.05(0.09)	3.71(0.03)	3.9 (0.1)	3.9 (0.2)	4.67(0.04)	2.52(0.06)	1.93(0.01)
	49.9	50.1	50.1	1.49(0.02)	0.84(0.03)	0.62(0.05)	5.13(0.06)	4.2 (0.1)	4.3 (0.2)	3.10(0.05)	1.56(0.03)	1.20(0.01)
2.00	1.56	1.69	1.62	648 (56)	26.3 (0.3)	5.93(0.28)	1.6 (0.1)	2.8 (0.2)	2.9 (0.2)	126 (7)	10.1 (0.5)	8.57(0.48)
	3.14	3.27	3.20	211 (28)	21.2 (1.0)	7.25(0.42)	0.75(0.05)	1.9 (0.1)	2.7 (0.1)	50 (2)	10.3 (0.2)	7.30(0.14)
	6.25	6.45	6.38	91 (5)	15.0 (0.1)	5.44(0.38)	1.8 (0.1)	1.51(0.06)	2.8 (0.1)	42.0 (0.8)	7.14(0.1)	5.37(0.06)
	12.7	12.8	12.7	17.5 (0.2)	5.25(0.07)	3.54(0.13)	2.3 (0.1)	2.38(0.04)	3.18(0.05)	15.8 (0.2)	4.56(0.01)	3.37(0.10)
	25.4	25.5	25.4	4.10(0.04)	1.88(0.02)	1.14(0.08)	3.5 (0.1)	3.4 (0.3)	3.6 (0.2)	5.84(0.05)	2.73(0.05)	2.06(0.06)
	39.7	39.8	39.7	1.98(0.03)	1.04(0.02)	0.71(0.07)	4.4 (0.1)	5.4 (0.2)	4.0 (0.1)	3.55(0.02)	1.76(0.02)	1.29(0.02)

Charge W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Negative Pressure[b] P^-_{so} (psi)			Negative Duration[b] $t^-_o/W^{1/3}$ ($msec/lb^{1/3}$)			Negative Impulse[b] $i^-_s/W^{1/3}$ ($psi\text{-}msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.36	2.68	2.68	c	2.0 (0.2)	1.8 (0.1)	c	11.5 (2.1)	11.1 (0.5)	c	15.5 (1.5)	9.2 (0.5)
	4.88	5.20	5.20	11.2 (1.6)	2.4 (0.5)	1.6 (0.1)	14.4 (2.8)	14.7 (3.1)	10.3 (1.0)	49.9 (6.5)	16.3 (2.6)	8.3 (0.5)
	9.92	10.2	10.2	3.4 (1.3)	1.5 (0.1)	1.07(0.03)	24 (2.7)	17.5 (1.3)	10.8 (0.9)	22.7 (2.4)	9.0 (0.5)	5.6 (0.2)
	20.3	20.3	20.3	1.3 (0.1)	0.61(0.03)	0.60(0.10)	19.8 (2.3)	18.0 (2.1)	10.9 (1.0)	8.6 (0.7)	4.1 (0.3)	3.4 (0.3)
	40.2	40.5	40.5	0.77(0.06)	0.36(0.01)	0.29(0.01)	12.0 (1.5)	18.6 (1.1)	11.4 (0.3)	4.9 (0.2)	2.24(0.06)	1.7 (0.1)
	62.8	63.2	63.2	0.33(0.01)	0.23(0.02)	0.20(0.01)	17.5(10.9)	25.6 (0.1)	12.0 (0.2)	2.4 (0.1)	1.46(0.06)	1.06(0.04)
1.00	1.88	2.13	2.13	c	2.9 (0.5)	2.0 (0.2)	c	11.7 (1.7)	12.4 (5.1)	c	14.7 (1.3)	9.9 (1.3)
	3.88	4.13	4.13	16.0 (1.6)	2.7 (0.4)	1.7 (0.1)	12.5 (0.6)	12.8 (0.4)	9.3 (2.0)	58 (9)	15.8 (0.5)	7.9 (0.4)
	7.88	8.13	8.13	4.0 (0.7)	1.7 (0.1)	1.13(0.05)	11.6 (4.2)	13.7 (0.6)	14.9 (2.6)	21.1 (2.1)	9.0 (0.5)	6.6 (0.2)
	15.9	16.1	16.1	1.7 (0.1)	0.9 (0.1)	0.65(0.02)	15.9 (0.1)	19.2 (5.0)	12.3 (0.4)	9.8 (0.5)	5.0 (0.5)	3.6 (0.1)
	31.9	32.1	32.1	1.0 (0.04)	0.44(0.03)	0.38(0.03)	9.8 (0.2)	13.7 (0.2)	9.0 (0.2)	4.8 (0.5)	2.25(0.05)	1.7 (0.1)
	49.9	50.1	50.1	0.41(0.02)	0.27(0.03)	0.24(0.02)	18.8 (0.8)	19.8 (0.4)	19.6 (2.4)	2.8 (0.1)	1.55(0.06)	1.3 (0.1)
2.00	1.56	1.69	1.62	c	3.0 (0.1)	1.9 (0.2)	c	9.2 (2.0)	12.9 (0.5)	c	12.9 (1.5)	10.3 (0.6)
	3.14	3.27	3.20	17.0 (4.6)	2.9 (0.1)	1.7 (0.1)	9.0 (2.2)	12.9 (0.9)	12.4 (0.8)	71 (12)	15.5 (0.9)	8.8 (0.2)
	6.25	6.45	6.38	5.6 (0.3)	1.7 (0.1)	1.22(0.06)	8.0 (0.7)	11.8 (1.6)	13.7 (1.2)	20.0 (0.5)	9.0 (0.4)	6.4 (0.2)
	12.7	12.8	12.7	2.2 (0.1)	1.0 (0.1)	0.64(0.03)	12.2 (1.4)	14.0 (0.1)	9.2 (0.3)	12.1 (0.5)	4.9 (0.4)	3.3 (0.1)
	25.4	25.5	25.4	1.1 (0.1)	0.46(0.02)	0.33(0.02)	9.3 (0.4)	18.9 (0.3)	15.8 (1.0)	5.0 (0.6)	2.7 (0.1)	2.1 (0.1)
	39.7	39.8	39.7	0.51(0.02)	0.29(0.02)	0.20(0.01)	10.0 (0.1)	14.5 (0.4)	18.3 (1.8)	2.74(0.06)	1.63(0.03)	1.30(0.04)

[a]Details of cubicle in Table 1 and Figure 4.

[b]Average of 5 measurements; number in parentheses is one standard deviation.

[c]Pressure too low to accurately resolve from pressure-time plot.

Table 7. Blast Environment Outside Large 3-Wall Cubicle With Roof[a]

Charge W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Positive Pressure[b] P_{so} (psi)			Positive Duration[b] $t_o/W^{1/3}$ ($msec/lb^{1/3}$)			Positive Impulse[b] $i_s/W^{1/3}$ ($psi \cdot msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.65	c	c	362 (19)	c	c	3.3 (0.7)	c	c	60 (15)	c	c
	5.16	5.04	5.09	55.8 (0.9)	9.40(0.57)	2.76(0.22)	2.9 (0.1)	3.7 (0.3)	5.7 (0.1)	45 (6)	10.3 (0.6)	6.51(0.32)
	10.2	10.0	10.1	26.8 (2.4)	6.07(0.41)	2.33(0.13)	2.8 (0.3)	3.5 (0.2)	5.6 (0.4)	26.4 (0.7)	9.65(0.28)	5.47(0.15)
	20.3	20.1	20.2	8.36(0.07)	3.53(0.11)	2.84(0.24)	4.9 (0.2)	3.9 (0.1)	5.0 (0.1)	13.2 (0.3)	5.55(0.10)	5.33(0.18)
	40.5	40.3	40.4	2.09(0.09)	1.43(0.04)	0.89(0.03)	5.2 (0.1)	4.8 (0.1)	6.0 (0.4)	5.10(0.10)	2.95(0.07)	2.25(0.03)
	63.0	63.0	63.1	1.05(0.02)	0.74(0.02)	0.59(0.01)	6.39(0.06)	5.5 (0.2)	6.4 (0.3)	3.02(0.05)	1.90(0.03)	1.48(0.02)
1.50	1.92	c	c	560 (150)	c	c	1.6 (0.1)	c	c	78 (10)	c	c
	3.63	3.49	3.45	109 (17)	16.7 (1.3)	4.28(0.14)	3.5 (0.7)	4.0 (0.2)	4.5 (0.2)	63 (8)	11.2 (0.7)	9.61(0.27)
	7.1	6.97	6.92	55.3 (1.5)	11.6 (0.7)	4.23(0.47)	2.5 (0.1)	3.47(0.04)	4.4 (0.2)	36.2 (1.1)	11.3 (0.2)	7.88(0.11)
	14.1	14.0	13.9	15.9 (1.3)	8.06(0.16)	4.29(0.26)	3.44(0.05)	3.9 (0.1)	4.16(0.02)	17.1 (0.8)	7.42(0.26)	7.71(0.22)
	28.1	28.0	28.0	3.62(0.09)	2.11(0.10)	1.72(0.08)	4.3 (0.1)	4.8 (0.2)	4.5 (0.2)	6.80(0.02)	3.83(0.05)	3.28(0.12)
	43.8	43.7	43.7	1.61(0.04)	1.13(0.06)	0.94(0.02)	5.13(0.04)	5.4 (0.1)	4.8 (0.1)	3.97(0.05)	2.54(0.05)	2.13(0.02)
3.00	1.56	c	c	361 (57)	c	c	1.3 (0.1)	c	c	83 (11)	c	c
	2.77	2.61	2.70	135 (13)	20.5 (1.6)	6.30(0.32)	2.3 (0.9)	3.3 (0.1)	3.9 (0.1)	67 (4)	10.7 (0.5)	10.9 (0.1)
	5.55	5.36	5.46	95.5 (12.6)	15.3 (1.2)	5.74(0.16)	2.4 (0.1)	2.67(0.03)	3.5 (0.1)	45.0 (3.6)	11.2 (0.4)	8.66(0.17)
	11.1	10.9	11.0	24.5 (1.4)	9.62(0.00)	5.21(0.19)	2.6 (0.1)	3.1 (0.1)	3.33(0.05)	19.4 (0.2)	8.01(0.12)	8.51(0.16)
	22.2	21.9	22.1	4.98(0.27)	2.78(0.13)	2.18(0.21)	3.85(0.06)	4.2 (0.3)	3.63(0.04)	7.79(0.14)	4.11(0.04)	3.55(0.06)
	34.7	34.5	34.6	2.16(0.15)	1.59(0.05)	1.28(0.06)	4.3 (0.2)	4.7 (0.1)	4.08(0.06)	4.46(0.03)	2.80(0.04)	2.34(0.03)

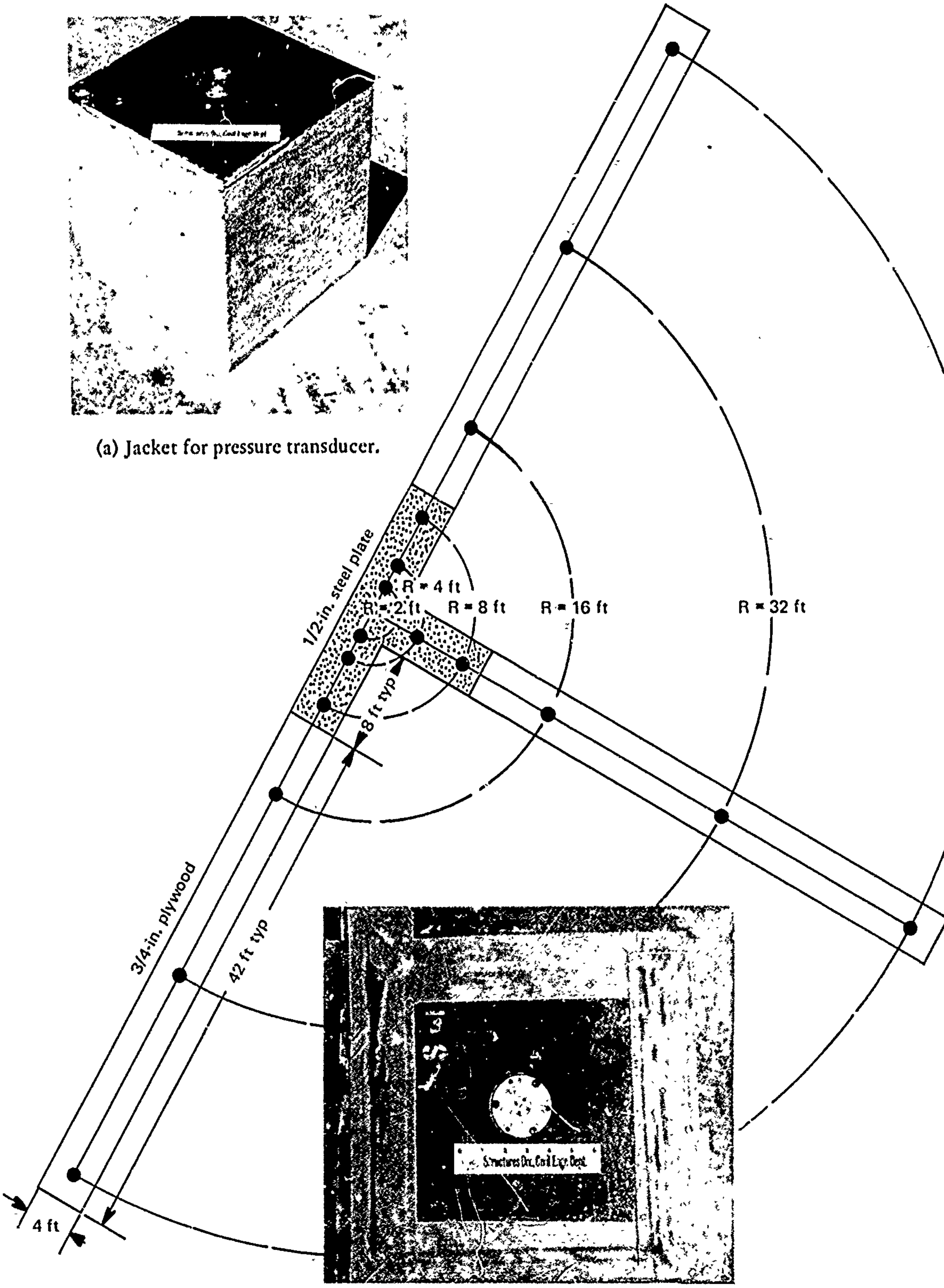
Charge W (lb)	Range, $R/W^{1/3}$ ($ft/lb^{1/3}$)			Negative Pressure[b] P_{so}^- (psi)			Negative Duration[b] $t_o^-/W^{1/3}$ ($msec/lb^{1/3}$)			Negative Impulse[b] $i_s^-/W^{1/3}$ ($psi \cdot msec/lb^{1/3}$)		
	Front	Side	Back	Front	Side	Back	Front	Side	Back	Front	Side	Back
0.50	2.65	c	c	d	c	c	d	c	c	d	c	c
	5.16	5.04	5.09	d	3.2 (0.3)	1.5 (0.1)	d	12.6 (1.7)	12.0 (0.7)	d	16.7 (1.4)	9.6 (0.5)
	10.2	10.0	10.1	3.7 (0.3)	2.0 (0.1)	1.2 (0.1)	11.2 (1.2)	12.4 (3.2)	12.0 (0.4)	22.8 (0.9)	11.4 (1.1)	7.6 (0.2)
	20.3	20.1	20.2	2.0 (0.1)	0.85(0.02)	1.2 (0.1)	11.1 (0.5)	13.5 (0.6)	12.4 (0.6)	13.7 (0.8)	6.0 (0.3)	3.3 (0.6)
	40.5	40.3	40.4	1.09(0.03)	0.42(0.01)	0.41(0.02)	11.3 (0.4)	11.6 (0.3)	10.6 (0.4)	7.5 (0.1)	3.0 (0.2)	2.9 (0.2)
	63.0	63.0	63.1	0.47(0.02)	0.25(0.01)	0.24(0.01)	11.2 (0.2)	12.0 (0.7)	11.5 (0.3)	3.42(0.03)	1.78(0.04)	1.8 (0.1)
1.50	1.92	c	c	d	c	c	d	c	c	d	c	c
	3.63	3.49	3.45	d	4.0 (0.4)	2.2 (0.1)	d	12.2 (0.7)	11.1 (0.3)	d	18.7 (0.6)	12.6 (1.0)
	7.1	6.97	6.92	4.1 (0.8)	3.0 (0.2)	1.73(0.05)	9.3 (1.8)	13.7 (0.2)	11.6 (0.2)	19.8 (2.2)	15.7 (0.4)	10.2 (0.8)
	14.1	14.0	13.9	2.1 (0.2)	1.34(0.08)	1.7 (0.1)	11.3 (0.4)	14.9 (0.6)	12.8 (0.2)	12.5 (0.9)	9.0 (0.7)	10.3 (1.5)
	28.1	28.0	28.0	1.2 (0.05)	0.57(0.03)	0.59(0.07)	12.5 (0.2)	17.6 (2.1)	10.4 (1.8)	7.2 (0.2)	4.2 (0.2)	3.8 (0.4)
	43.8	43.7	43.7	0.54(0.01)	0.37(0.02)	0.39(0.01)	14.7 (0.1)	16.3 (0.1)	12.8 (0.2)	3.9 (0.1)	2.5 (0.1)	2.4 (0.1)
3.00	1.56	c	c	d	c	c	d	c	c	d	c	c
	2.77	2.61	2.70	d	4.3 (0.5)	2.1 (0.1)	d	d	9.0 (0.9)	d	d	12.1 (0.6)
	5.55	5.36	5.46	3.8 (0.3)	2.7 (0.3)	1.9 (0.2)	6.3 (1.2)	d	9.1 (0.3)	14.1 (1.9)	d	9.7 (0.3)
	11.1	10.9	11.0	2.5 (0.2)	1.4 (0.1)	1.8 (0.1)	9.4 (0.1)	14.5 (1.1)	14.2 (0.3)	11.4 (0.6)	9.7 (0.4)	11.3 (0.5)
	22.2	21.9	22.1	1.4 (0.1)	0.63(0.05)	0.66(0.05)	10.6 (0.3)	15.7 (0.2)	11.0 (1.2)	5.9 (0.4)	7.9 (0.1)	3.8 (0.1)
	34.7	34.5	34.6	0.64(0.02)	0.44(0.02)	0.40(0.04)	7.9 (0.5)	15.5 (0.2)	10.8 (1.5)	4.2 (0.1)	2.6 (0.1)	2.6 (0.1)

[a] Details of cubicle in Table 1 and Figure 4.

[b] Average of 5 measurements; number in parentheses is one standard deviation.

[c] No pressure transducer at this location.

[d] Data resolution not sufficient to accurately measure value.



(a) Jacket for pressure transducer.

(b) Pressure transducer in place.

Figure 8. Test site and pressure transducers.

Partially Vented Explosions

Plots in Figures A-1 through A-4 are representative of the blast environment measured inside the 4-wall cubicles and show the effects of charge weight and vent area. Peak gas pressure P_g increases with increasing charge weight, and gas pressure duration t_g increases with decreasing vent area. Impulse, also shown in these figures, is affected by both charge weight and vent area.

Plots in Figures A-5 through A-10 are representative of the blast environment outside 4-wall cubicles. Peak pressure P_{so} and inpulse i_s are shown to increase with increasing charge weight and vent area.

Appendix A includes a detailed description of the data plots.

Fully Vented Explosions

Plots in Figures A-11 through A-34 are representative of pressure measurements outside the fully vented 3-wall cubicles with and without roofs. The plots are arranged for ease in comparing results at a fixed distance in each of three directions from the cubicle (out the front, behind the sidewall, and behind the backwall). Eighteen plots are shown in six figures (each of six gage locations in each direction) for each cubicle configuration (S3W, L3W, S3WR, L3WR).

In a few tests of L3W, measurements were also taken within the cubicle. Sample results from these tests are shown in Figures A-35 and A-36.

Appendix A includes a detailed description of these plots.

ANALYSIS OF PARTIALLY VENTED EXPLOSIONS

Explosions generate shock pressures from shock waves emitted by the detonation. If the explosion is confined inside an enclosed or partially vented cubicle, the heat energy released by the detonation and subsequent afterburning raises temperatures of the air and gaseous by-products of the explosion and thereby generates gas pressures, in addition to the shock pressures. The initial shock wave strikes the walls of the cubicle and is reflected. The reflected waves, bouncing back and forth between the walls, floor, and roof, produce extremely high blast pressures on the walls. The blast pressures rapidly decay as the energy in the shock wave rapidly dissipates.

In the same time period, the gas pressures rise inside the cubicle to some peak value and then gradually decay as gas temperatures drop and gas pressures are vented from the cubicle. The peak gas pressure is characteristically small compared to the peak blast pressure. However, the duration of the gas pressure can be many times greater than the duration of the blast pressure when the vent area is small. If the vent area is increased, the duration of the gas pressure will decrease. At some critical vent area, the duration of the gas pressure will essentially equal the duration of the blast pressure. At that point, the gas pressure will be insignificant. This critical vent area can define the division between a fully and partially vented explosion. Further increase in the vent area will not appreciably change the pressure loading on the walls, floor, and roof of the cubicle.

Outside the cubicle, the shock waves escaping from the cubicle through the vent area generate a train of shock waves which expand and travel outward in all directions from the cubicle. The number of shock waves and their energy content appear to be very erratic, although they are reproducible between tests. The erratic pattern is due apparently to the random but repetitive nature of the multiple shock reflections off the faces of the cubicle. Consequently, the pressure-time history outside the cubicle contains pronounced multiple pressure spikes. The number of pressure spikes is consistently greatest at small scaled distances and reduces with distance as the shock waves in the rear of the train overtake and merge with the leading waves. This merging process continues with distance until at some range there is one major wave, although a few distinct pressure spikes may still persist at large, scaled distances. In almost every case, the first pressure spike is greatest and succeeding spikes diminish in magnitude. At far ranges from the cubicle, the shock waves produce a pressure-time history characteristic of the shape from an unconfined explosion, except that the peak pressure and impulse are less.

Blast Environment Inside Cubicle

For partially vented explosions, the gas pressure duration inside the cubicle is often large relative to the fundamental period (T_n) of the walls and roof, particularly if the vent area is small. By comparison, the duration of the blast pressure is often small relative to the fundamental period of the walls. In this case, the gas pressure can be far more damaging to the cubicle than the blast pressure, even though the peak gas pressure is often much lower than the peak blast pressure. Therefore, the cubicle must be designed for the gas pressure pulse, as well as the blast pressure pulse, if collapse of the cubicle, secondary fragments, or propagation of the explosion must be avoided. To accomplish this, the designer needs a method to predict the magnitude, duration, and total impulse of the gas pressures for a given shape, size, and vent area of a cubicle containing a given composition and weight of explosive. Charts and equations relating to these parameters, based on the experimental data, are explored in the following sections.

Peak Gas Pressure. The rise in temperatures of the ambient air and gaseous by-products of the explosion generates gas pressures in the cubicle. Proctor and Filler at NOL (Naval Ordnance Laboratory) have applied explosion theory to predict these gas pressures in enclosed chambers [3,4]. From perfect gas laws and the chemistry of explosives they computerized an iterative procedure which analytically follows the energy generation of the chemical reactions and the changes in gas properties as gas pressure and temperatures rise inside the cubicle. Predicted peak gas pressures from the NOL program account for the weight and chemical composition of the explosive, the volume within which the explosion is confined, and the properties of the ambient gas inside the cubicle. Peak gas pressures calculated by the NOL program correlate remarkably well with experimental data gathered by H.R.W. Weibull [5], as shown in Figure 9. Weibull's data is based on TNT charges detonated inside spheres, tubes, and cubes for a wide range of charge-to-volume ratios ($0.00125 < W/V < 0.287$ lb/ft^3) but relatively small vent areas ($8 \times 10^{-5} < A/V^{2/3} < 0.02$). The dashed lines in Figure 9 indicate theoretical results if either heat-of-combustion or heat-of-detonation values for TNT are used with a fixed specific heat. The NOL theoretical relationship is based on an iterative solution that accounts for variable specific heat (as a function of temperature) during the gas pressure buildup. At the point corresponding to a gas pressure of about 250 psi there is an inflection in the curve when the oxygen in the ambient air is no longer adequate to completely burn the explosion products. In this region the curve drifts toward the heat of detonation line where the curve again begins to increase at roughly the initial slope.

Figure 10 shows the peak gas pressures measured inside cubicle S4WPR as a function of W/V. Included in Figure 10 are experimental data reported by Ferritto [6] who detonated composition B charges inside a relatively large 4-wall cubicle with a circular hole in its roof. Ferritto varied W/V from 0.0016 to 0.0259 lb/ft^3, as outlined in Table 2. The gas pressure curve predicted by the NOL computer program for composition B explosive is also shown in Figure 10. The correlation between measured and predicted values is not as good as the excellent agreement shown in Figure 9. But it is important to note that Weibull's test data is for scaled venting of $8 \times 10^{-5} < A/V^{2/3} < 0.02$, while the CEL scaled venting was $0.008 < A/V^{2/3} < 0.18$. For larger charge densities ($W/V > 0.07$), the data points in Figure 10 fall well below the predicted curve; and, for a fixed degree of scaled venting, the difference increases with W/V. For example, for points with $A/V^{2/3} = 0.179$ and 0.060, the measured gas pressures are lower by 27% at $W/V = 0.0069$, 31% at $W/V = 0.069$, 39% at $W/V = 0.145$, and 52% at $W/V = 0.287$. Some of the differences may stem from possible errors in interpreting the measured pressure-time histories, but this source of error could account for no more than perhaps 20% of the difference.

It is concluded from Figure 10 that peak gas pressures depend on both the charge-to-volume ratio and the degree of venting. Peak gas pressure increases with W/V and decreases with increased venting. For $W/V < 0.02$, venting has no appreciable influence on P_g; but for greater W/V ratios the decrease in P_g can be significant. Experiments should be conducted to find the relationship for the peak gas pressure in a partially vented cubicle as a function of $A/V^{2/3}$ and W/V, for $A/V^{2/3} > 0.010$ and $0.001 < W/V < 0.300$. Until this relationship is found, it is recommended

that the NOL curve for gas pressure be used for design loads for $A/V^{2/3} < 0.010$ and a value 25% less for $A/V^{2/3} > 0.010$.

Duration of Gas and Shock Pressures. The scaled duration of positive pressure inside the cubicles, listed in Table 2, is plotted in Figure 11 as a function of the scaled vent area $A/W^{2/3}$. Data points in Figure 11 are either shaded or unshaded to distinguish between gas and shock durations. The unshaded data points denote cases where the duration of the gas pressure t_g exceeded the duration of the shock pressure t_o; pressure-time histories shown in Figure A-1 are representative of this case. The shaded data points denote the case where it appears that $t_o > t_g$; pressure-time histories shown in Figures A-4, A-35, and A-36 are representative of this case. Actually, some of the low-pressure fluctuations shown in Appendix A may indeed be caused by fluctuations in gas pressures instead of multiple shock reflections, although the latter cause seems more reasonable.

The family of lines shown in Figure 11 connect data points representing the same value of W/V. The solid lines are straight, parallel, and connect data points corresponding to $t_g > t_o$. The equation of these lines is

$$\frac{t_g}{W^{1/3}} = 2.26\left[\left(\frac{A}{W^{2/3}}\right)\left(\frac{W}{V}\right)\right]^{-0.86} \qquad (1a)$$

for $A/V^{2/3} < 0.21$

The dashed lines connect data points believed to correspond to $t_o > t_g$. The dashed lines also are straight and parallel but their slopes are greater. The equation of these lines is

$$\frac{t_o}{W^{1/3}} = 0.664\left[\left(\frac{A}{W^{2/3}}\right)\left(\frac{W}{V}\right)\right]^{-1.14} \qquad (2a)$$

for $A/V^{2/3} > 0.60$

Between the ends of the solid and dashed lines in Figure 11 is a transition zone which identifies the transition from $t_g > t_o$ to $t_g < t_o$. There is insufficient experimental data to exactly identify the transition zone, but for each value of W/V there should exist one value of $A/W^{2/3}$ corresponding to $t_g = t_o$. The line for $t_g = t_o$ would be represented in Figure 11 by some line oblique to the family of solid and dashed lines. The oblique line must lie somewhere "below" the unshaded data points ($t_g > t_o$) and "above" the shaded data points ($t_o > t_g$).

The influence of cubicle geometry on the duration of positive pressure inside the cubicle is conveniently described by the parameter $A/V^{2/3}$. Note that $A/V^{2/3}$ is independent of charge weight and a dimensionless parameter and, therefore, independent of the physical size of the cubicle and charge. It was found that $A/V^{2/3}$ is a convenient parameter for bounding the transition zone corresponding to $t_g = t_o$. For example, Equation 1a can be expressed as

$$\frac{t_g}{W^{1/3}} = 2.26\left[\frac{\left(A/V^{2/3}\right)^3}{A/W^{2/3}}\right]^{-0.86} \qquad (1b)$$

Equation (1b) is plotted in Figure 11 for $A/V^{2/3} = 0.21$. The line is oblique to the lines described by Equation 1a and falls just below the unshaded data points; $A/V^{2/3} = 0.21$ is considered a reasonable upper bound to the transition zone corresponding to $t_g = t_o$. Similarly, Equation 2a can be expressed as

$$\frac{t_o}{W^{1/3}} = 0.664\left[\frac{\left(A/V^{2/3}\right)^3}{A/W^{2/3}}\right]^{-1.14} \qquad (2b)$$

Equation 2b is plotted in Figure 11 for $A/V^{2/3} = 0.60$, 1.00 (4-wall cube with no roof), and 2.00 (3-wall cube with no roof). The line for $A/V^{2/3} = 0.60$ falls just above the shaded data points and is considered a reasonable lower bound to the transition zone corresponding to $t_g = t_o$.

To illustrate the significance of the parameter $A/V^{2/3}$, consider a perfect cube with four walls and a partial roof. To ensure $t_o > t_g$, the vent area A must be greater than $0.60V^{2/3} = 0.60L^2$, or greater than 60% of the roof area must be vented. It should be emphasized that the above relationships are only approximate because the exact value of $A/V^{2/3}$ corresponding to $t_g = t_o$ is unknown. Further, Equation 2a and 2b are based on charges located at the geometric center of the cubicle. Equation 3 should be used for other charge locations. Equations 1a and 1b should not be significantly affected by charge location.

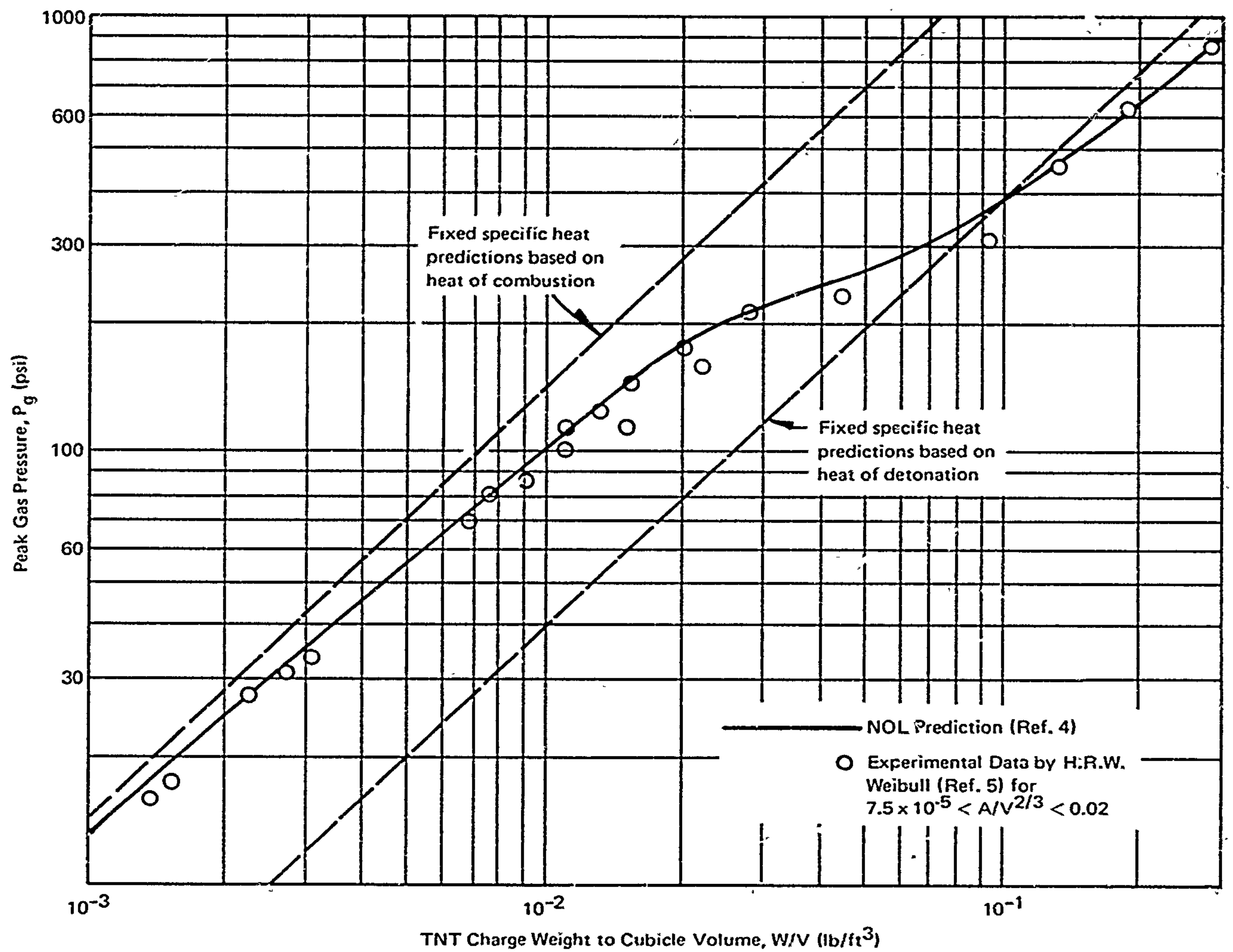


Figure 9. Peak-gas pressure from a partially vented explosion of TNT in a 4-wall cubicle.

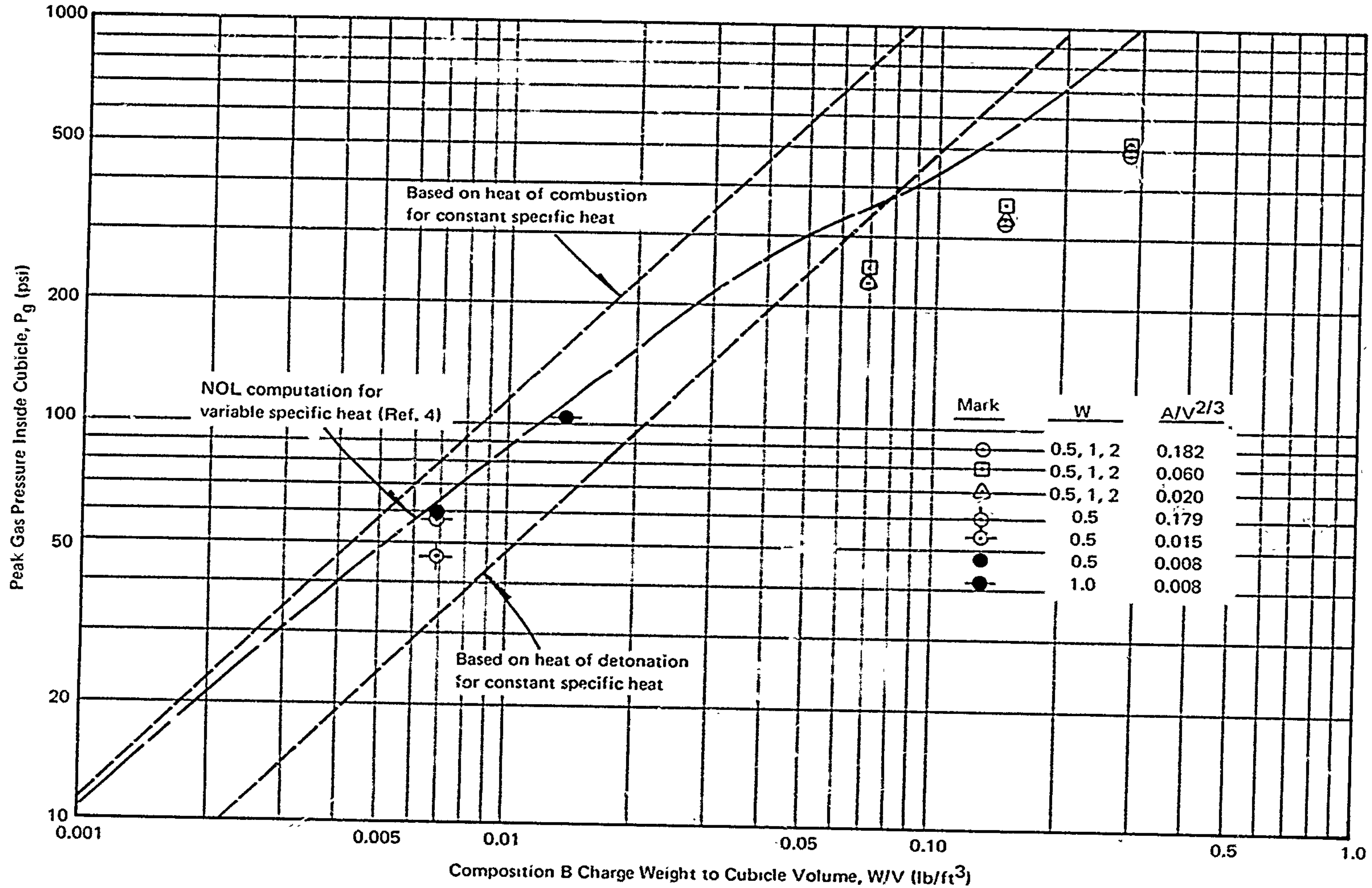


Figure 10. Peak gas pressure from a partially vented explosion of composition B in a 4-wall cubicle.

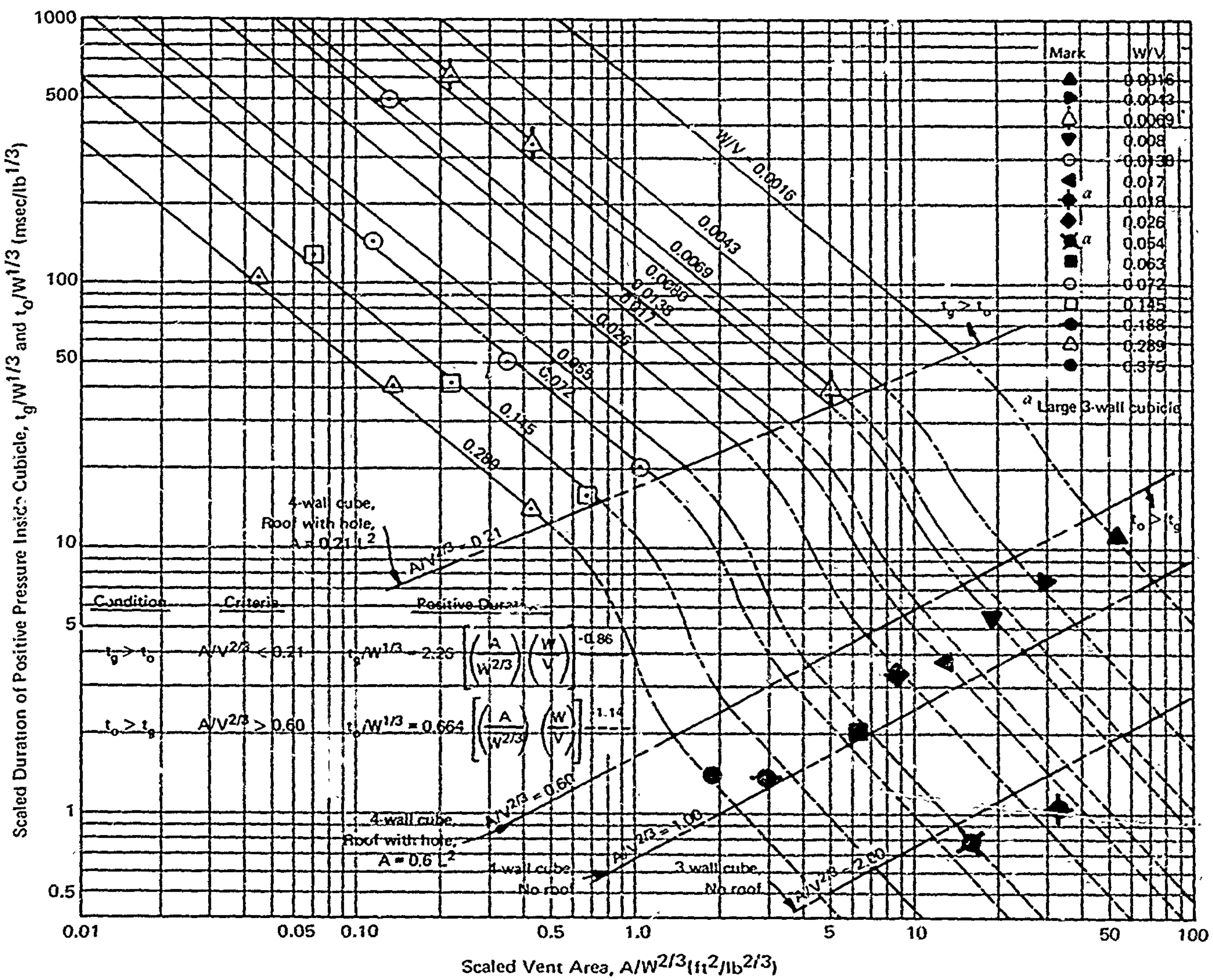


Figure 11. Scaled duration of positive pressure inside cubicle versus scaled vent area and cubicle volume.

The product of the scaled vent area $A/W^{2/3}$ and scaled volume W/V is equal to the scaled degree of venting $A\,W^{1/3}/V$. Therefore, Equations 1a and 1b can be expressed as

$$\frac{\tau_g}{W^{1/3}} = 2.26\left(\frac{A\,W^{1/3}}{V}\right)^{-0.86} \qquad (1)$$

for $A/V^{2/3} < 0.21$

$$\frac{t_o}{W^{1/3}} = 0.664\left(\frac{A\,W^{1/3}}{V}\right)^{-1.14} \qquad (2)$$

for $A/V^{2/3} > 0.60$

Equations 1 and 2 are compared with experimental data in Figure 12. As expected, the unshaded data points fall along the solid line describing Equation 1 and the shaded data points fall along the dashed line describing Equation 2. The transition zone, defined in Figure 11 by $0.21 < A/V^{2/3} < 0.60$, falls between these lines and is represented in Figure 12 by a series of reverse curves which are tangent to the solid and dashed lines. Note that the relative position of the transition lines depends on W/V. For $0.21 < A/V^{2/3} < 0.60$, one must enter Figure 12 with known values of both $AW^{1/3}/V$ and W/V to determine the duration of the positive pressure. It should be emphasized again that values of $t_o/W^{1/3}$ are based on the charge located at the geometric center of the cubicle.

In the Army TM 5-1300 Design Manual, the duration of the shock pressure on the wall of a cubicle is calculated from

$$t'_o = (t_A)_F - (t_A)_N + 1.5(t_o)_F \qquad (3)^*$$

where t'_o = design duration of the positive pressure phase, msec.

$(t_A)_F$ = time of arrival of the blast wave at the point on the wall farthest from the charge, R_F.

$(t_A)_N$ = time of arrival of the blast wave at the point on the wall nearest to the charge, R_N.

$(t_o)_F$ = duration of the blast pressure at the point on the wall farthest from the charge, R_F.

1.5 = a factor to account for the increased load duration on the wall due to the multiple reflections of the blast wave within the cubicle.

The procedure for solving Equation 3 involves computing the scaled distances to the far point on the wall ($R_F/W^{1/3}$) and the nearest point on the wall ($R_N/W^{1/3}$) and then entering the air burst curves of Figure 4-5 of Reference 1 to determine the times given in Equation 3.

For a rectangular- or cube-shaped cubicle with the charge located at the geometric center of the cubicle, it can be shown that Equation 3 depends on the charge-to-volume ratio W/V and the aspect ratios of the cubicle [7]. For a sidewall (shortest wall of a 3- or 4-wall cubicle),

$$\left(\frac{t'_o}{W^{1/3}}\right)_s = \left(\frac{t_A}{W^{1/3}}\right)_F - \left(\frac{t_A}{W^{1/3}}\right)_N + 1.5\left(\frac{t_o}{W^{1/3}}\right)_F \qquad (4)$$

If the charge is located at the geometric center of the cubicle, the scaled distances to the far and near points of the sidewall (for entering Figure 4-5 of Reference 1) can be expressed by

$$\frac{R_F}{W^{1/3}} = \frac{\left[1+\left(\frac{L_s}{H}\right)^2+\left(\frac{L_b}{H}\right)^2\right]^{1/2}}{2\left[\left(\frac{L_s}{H}\right)\left(\frac{L_b}{H}\right)\right]^{1/3}\left(\frac{W}{V}\right)^{1/3}} \qquad (4a)$$

$$\frac{R_N}{W^{1/3}} = \frac{\frac{L_b}{H}}{2\left[\left(\frac{L_s}{H}\right)\left(\frac{L_b}{H}\right)\right]^{1/3}\left(\frac{W}{V}\right)^{1/3}} \qquad (4b)$$

In Figure 13 the positive duration of the shock pressure predicted by Equation 4 is compared with that predicted by Equation 2. Figure 13a compares the predicted shock duration on the sidewall of a perfect 3-wall cube, 4-wall cube with an open top, and a 4-wall cube with a partial roof. Figure 13b

* Equation 4-1 from Reference 1.

compares the predicted shock duration on the sidewall of the rectangular 3-wall cubicle tested at the Naval Ordnance Test Station (NOTS) China Lake* [2] and shows how the shock duration would be affected, according to Equation 2b, by adding a fourth wall and partial roof.

In Figure 13, note that $t_0'/W^{1/3}$ computed from Equation 4 depends only on the size and position of the sidewall relative to the charge weight. Consequently, Equation 4 does not account for the number or size of reflecting walls or surfaces comprising the cubicle. By comparison, Equation 2 shows that $t_0/W^{1/3}$ increases as the number and size of reflecting surfaces is increased. Equations 2 and 4 are in good agreement for a 3-wall cube (the case for which Equation 2 was derived) only for values of $W/V < 0.02$. For the rectangular NOTS cubicle, the agreement is best for the 4-wall case.

The actual shock pressure on the wall of a cubicle decays exponentially with time. For convenience in design, this exponential pulse is replaced by an equivalent triangular-shaped, pressure-time pulse having the same total impulse. Equation 3 is intended to approximate the duration of the equivalent triangular pulse while Equation 2 is the duration of the exponential pulse. Therefore, $t_0'/W^{1/3}$ given by Equation 4 should always be less than that given by Equation 2. Indeed this is the trend shown in Figure 13, except for small values of W/V in 3-wall cubicles. Actually, Equation 3 is probably too conservative for 4-wall cubicles with or without a roof because it tends to force the designer to treat the shock pressure pulse as an impulse when in reality it is much less severe. One solution to correct this situation is to make the factor 1.5 in Equation 3 a variable which changes, depending upon the number and size of reflecting surfaces.

Impulse of Gas Pressure. The scaled peak impulse of the gas pressure measured inside the cubicles, listed in Table 2, is plotted in Figure 14 as a function of the scaled vent area, $A/W^{2/3}$. The unshaded data points denote cases where the total impulse of the gas pressure i_g far exceeded the total impulse of the shock pressure i_s.

The family of lines shown in Figure 14 connect data points having the same value of W/V. The best-fit lines are straight and parallel, at least within the range of the experimental data. The lines are described by

$$\frac{i_g}{W^{1/3}} = 569\left(\frac{A}{W^{2/3}}\right)^{-0.78}\left(\frac{W}{V}\right)^{-0.38} \qquad (5)$$

for $A/V^{2/3} < 0.21$

Equation 5 has some error because it is derived from impulse data which include the combined impulse from the gas pressure and a portion of the shock pressures. However, any error in Equation 5 from this source is considered insignificant since all data points in Figure 14 originate from pressure-time histories, represented by Figures A-1, A-2, A-3, and A-4 which clearly show the shock impulse was insignificant compared to the gas impulse.

There is no experimental data to define the exact shape of the lines in Figure 14 for $0.21 < A/V^{2/3} < 0.60$. To provide compatability with the curves in Reference 1 for a fully vented cube, the shape of the dashed lines in Figure 14 were drawn so that at $A/V^{2/3} = 0.60$, the duration of the shock pressure t_0' given by Equation 3 (Equation 4-1 of Reference 1) is equal to the fictitious duration of the gas pressure, $t_g' = 2i_g/P_g$. By this scheme, the impulse curves in Figure 14 provide a smooth transition from a partially vented cube to a fully vented cube and are compatible with the pressure loading obtained from Reference 1 for a fully vented cube.

The TM 5-1300 Design Manual contains a series of charts (Figures 4-17 through 4-62) for predicting the average shock impulse i_s acting on the walls of a cubicle of any size and shape. For the special case of a perfect cube with the charge located at the geometric center of the cube, it can be shown that, according to the charts, the average scaled shock impulse $i_s/W^{1/3}$ acting on a wall is a function of W/V and the number of adjoining walls N [7]. This relationship for a cube is shown in Figure 15 for N = 4. Also shown in Figure 15 is $i_g/W^{1/3}$ from Equation 5 for a 4-wall cube with a partial roof where $A/V^{2/3} = 0.21$. The two curves in Figure 15 serve to illustrate the error in the predicted loading on a wall for a range of W/V if the calculations include i_s from Reference 1 but neglect the gas impulse i_g from Figure 14.

* Now the Naval Weapons Center (NWC).

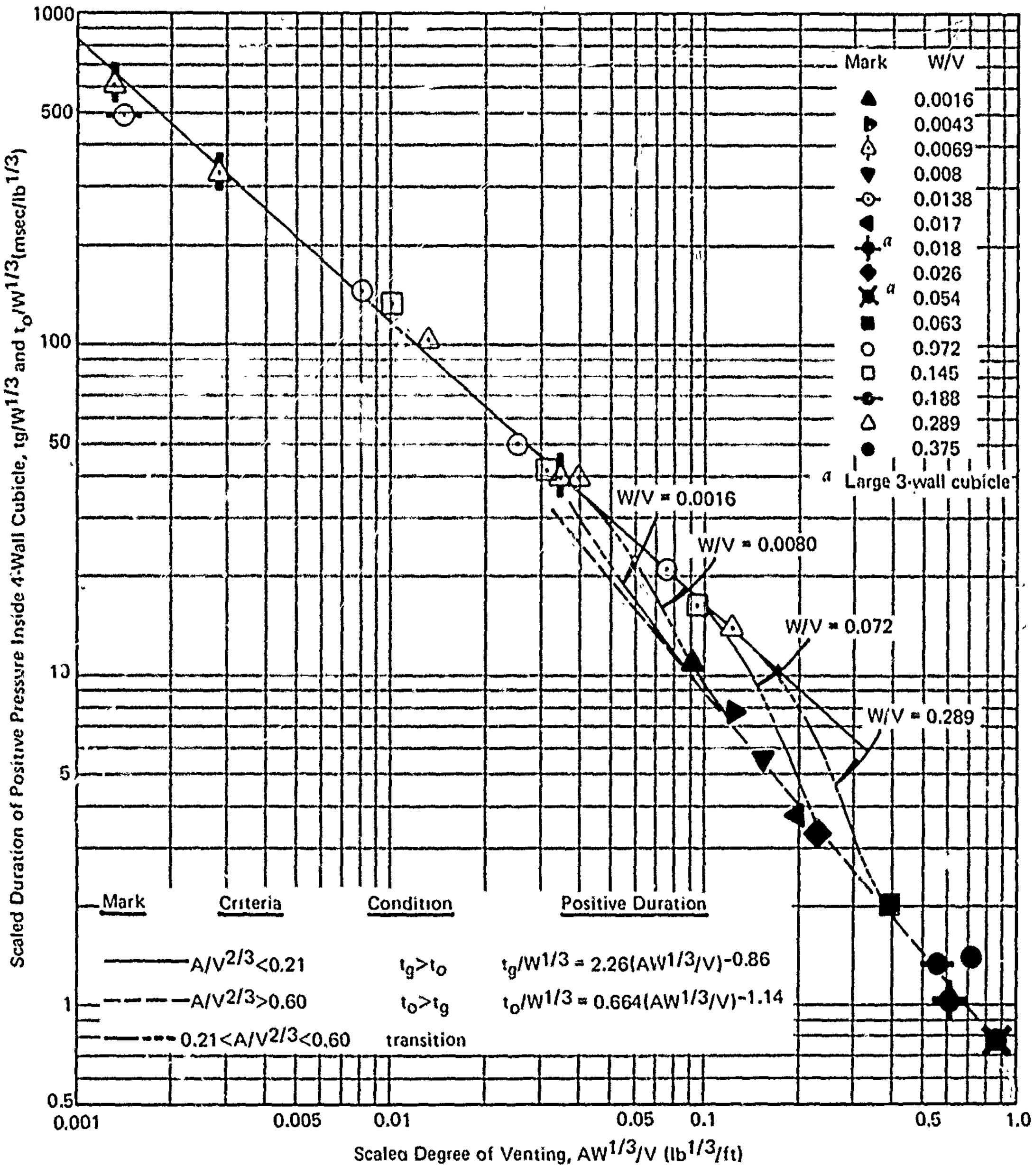
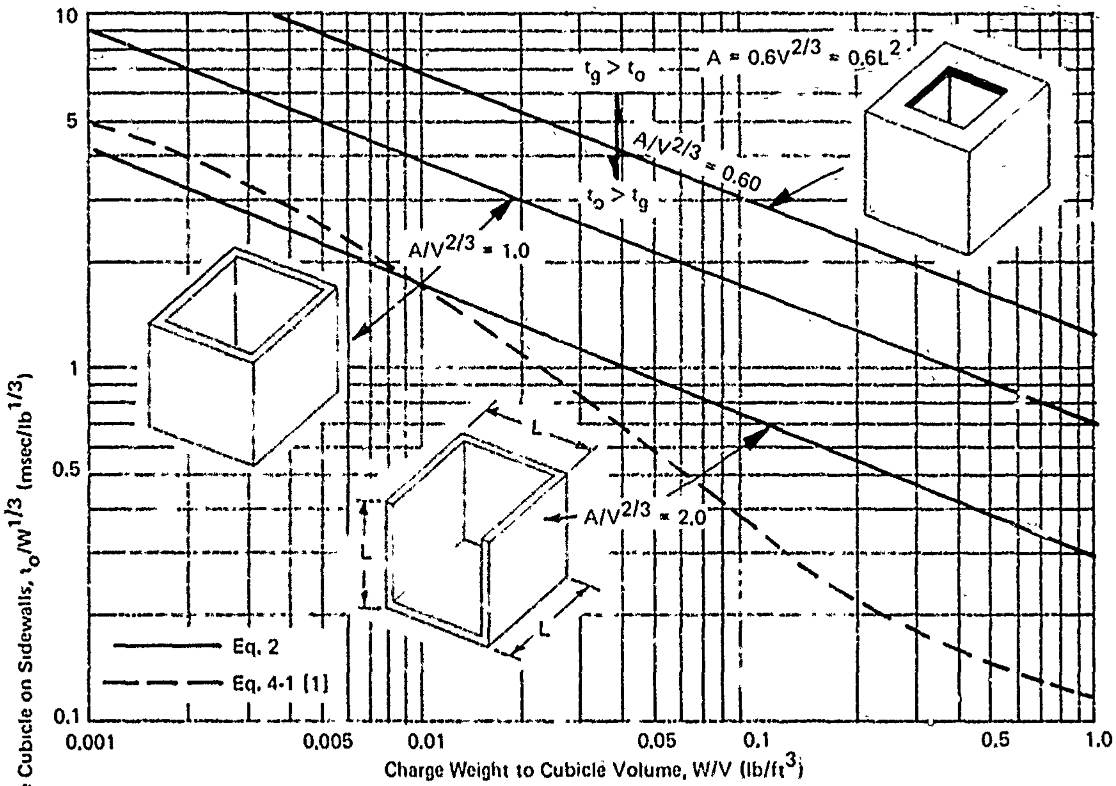
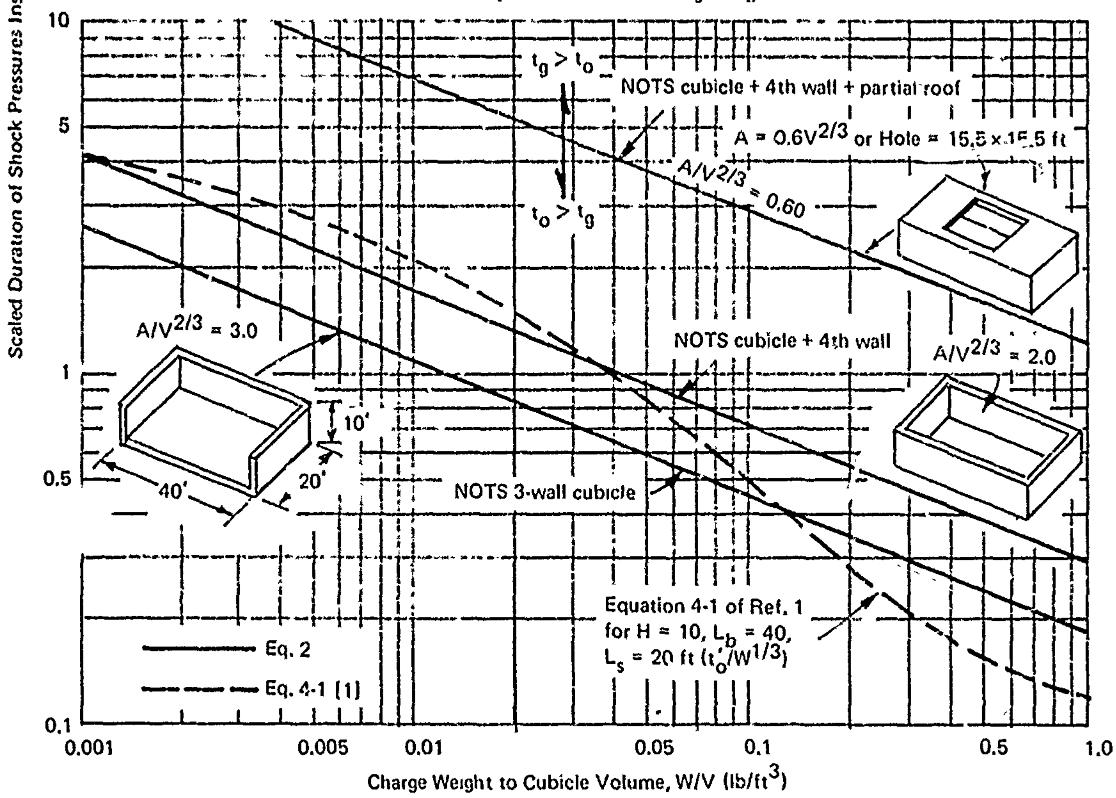


Figure 12. Design chart for scaled duration of positive pressure inside cubicle versus scaled degree of venting.



(a) For a perfect cube ($H = L_s = L_b$).



(b) For NOTS full-scale cubicle (H = 10, L_b = 40, L_s = 20 feet).

Figure 13. Duration of shock pressure on wing wall of a cubicle compared with Equation 4-1 of Reference 1.

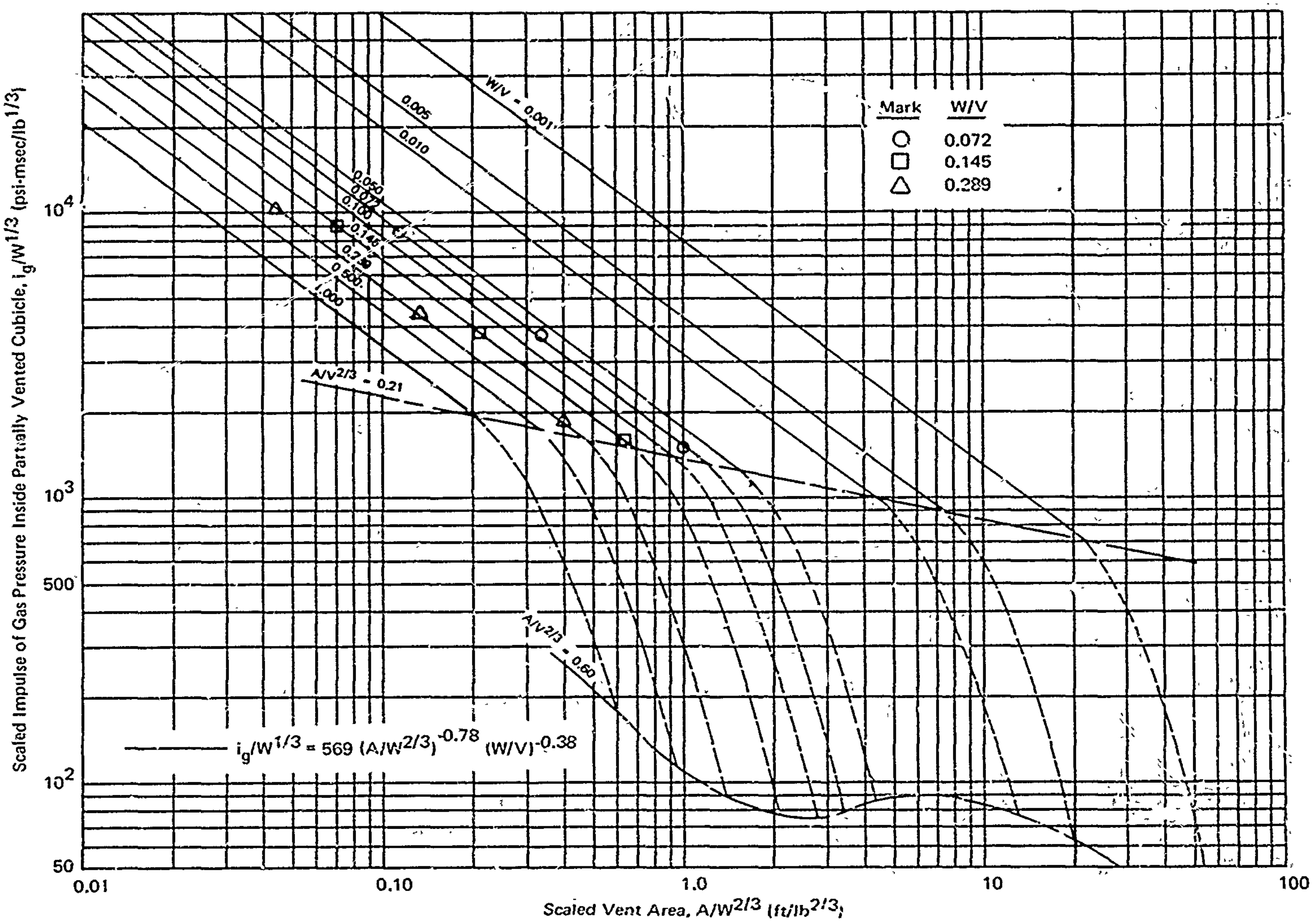


Figure 14. Scaled impulse of gas pressure inside a partially vented cubicle.

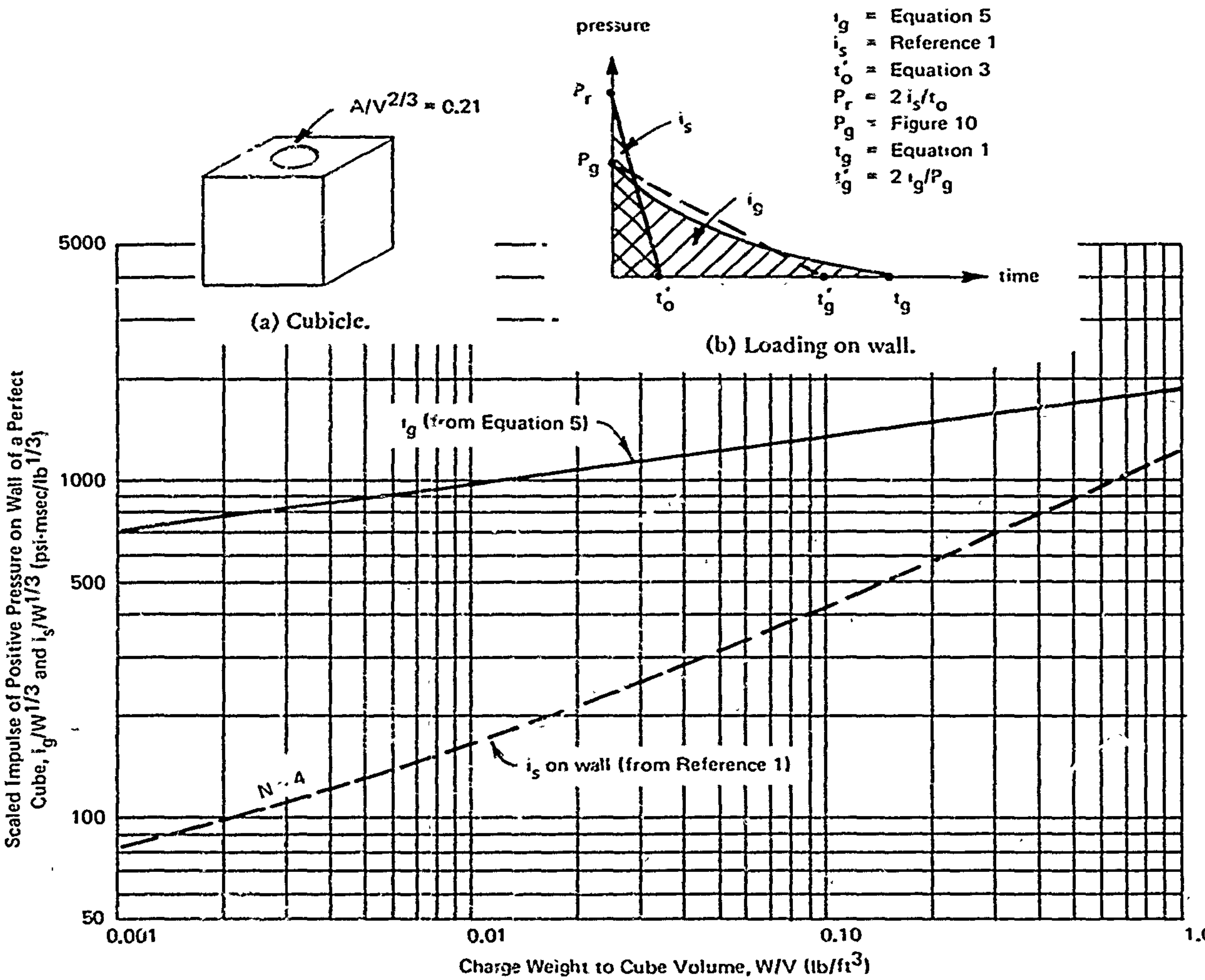


Figure 15. Loading on the wall of a perfect cube for $A/V^{2/3} = 0.21$.

The following problems and their solutions serve to illustrate the use of the various charts to construct the pressure-time loading, shown in Figure 15b, on the wall of a partially vented cubicle. The first problem illustrates the case where the gas pressures dominate the loading function on the wall. The second problem illustrates the case where the shock pressures dominate the loading on the wall.

Problem 1. A 4-wall cube with a hole in its roof contains 17 pounds of composition B explosive located at the geometric center of the cubicle. The length of each wall is 10 feet. The vent hole in the roof is 3.0 feet in diameter. Is the cubicle partially vented? Calculate the pressure-time loading (Figure 15b) acting on a wall.

Solution. Given W = 17 pounds, $A = \pi D^2/4 = \pi(3.0)^2/4 = 7.1$ ft^2 and $V = 10 \times 10 \times 10 = 1{,}000$ ft^3. Therefore, $A/V^{2/3} = 7.1/(1{,}000)^{2/3} = 0.07$, $W/V = 17/1{,}000 = 0.017$ and $A/W^{2/3} = 7.1/(17)^{2/3} = 1.07$. Since $A/V^{2/3} \leq 0.60$, the cubicle is partially vented and gas pressures must be considered in the wall loading. From Figure 10, $P_g = 135$ psi. From Figure 11, $t_g/W^{1/3} = 70$ or $t_g = 70(17)^{1/3} = 180$ msec. From Figure 14, $i_g/W^{1/3} = 2{,}540$ or $i_g = 2{,}540\,(17)^{1/3} = 6{,}530$ psi-msec. For design purposes, the fictitious gas duration is $t_g' = 2i_g/P_g = 2(6{,}530)/135 = 97$ msec. From Reference 1 or Figure 15, $i_s/W^{1/3} = 200$ or $i_s = 200\,(17)^{1/3} = 514$ psi-msec. From Equation 4-1 of Reference 1 or Figure 13a, $t_0'/W^{1/3} = 1.3$ or $t_0' = 1.3(17)^{1/3} = 3.3$ msec. For design purposes, the fictitious peak shock pressure is $P_r = 2i_s/t_0' = 2(514)/3.3 = 311$ psi. The calculated pressures, impulses, and time durations apply to the load diagram shown in Figure 15b.

Problem 2. The vent hole in the roof of the cubicle described in Problem 1 is increased to 8.75 feet in diameter. Is the cubicle fully vented? Calculate the pressure-time loading (Figure 15b) acting on a wall.

Solution. Given W = 17 pounds, $A = \pi D^2/4 = \pi(8.75)^2/4 = 60$ ft^2 and $V = 10 \times 10 \times 10 = 1{,}000$ ft^3. Therefore, $A/V^{2/3} = 60/(1{,}000)^{2/3} = 0.60$, $W/V = 17/1{,}000 = 0.017$ and $A/W^{2/3} = 60/(17)^{2/3} = 9.1$. Since $A/V^{2/3} \geq 0.60$, the cubicle is fully vented and no gas pressure must be considered in the design loading, as confirmed by the following calculations. From Figure 10, $P_g = 135$ psi. From Figure 11, $t_g/W^{1/3} = 5.6$ or $t_g = 5.6(17)^{1/3} = 14.4$ msec. From Figure 14, $i_g/W^{1/3} = 87$ or $i_g = 87(17)^{1/3} = 223$. For design purposes, the fictitious gas duration is $t_g' = 2i_g/P_g = 2(223)/135 = 3.3$ msec. From Reference 1 or Figure 15, $i_s/W^{1/3} = 200$ or $i_s = 200(17)^{1/3} = 514$ psi-msec. From Equation 4-1 of Reference 1 or Figure 13a, $t_0'/W^{1/3} = 1.3$ or $t_0' = 1.3(17)^{1/3} = 3.3$ msec. For design purposes, the fictitious peak shock pressure is $P_r = 2i_s/t_0' = 2(514)/3.3 = 311$ psi. Note that $t_g > t_0$ but $t_g' \leq t_0'$ and therefore the cubicle can be considered as fully vented and the design can be based solely on P_r and t_0. The calculated pressures, impulses, and time durations apply to the load diagram shown in Figure 15b.

Blast Environment Outside Cubicle

Personnel or frangible buildings may be located in the near vicinity of a cubicle containing explosives. An accidental explosion may produce a blast environment outside the cubicle which constitutes a high hazard to personnel or an unacceptable level of damage to the buildings. In this case, it may be necessary to partially confine the explosion inside a cubicle to reduce the blast environment to a safe level. To accomplish this, the designer must know the influence of the cubicle geometry and the charge weight, location, and composition on the blast environment outside the cubicle. The influence of some of these parameters on the positive and negative pressures, impulses, and durations outside a cubicle containing a partially vented explosion are explored in subsequent sections.

Peak Positive Pressure. Consider an explosion inside a 4-wall cubicle with a relatively small hole in its roof, similar to cubicle S4WPR. Detonation of the charge produces an initial shock wave followed by the buildup of gas pressures inside the cubicle. The initial shock wave expands and reflects back and forth between the walls, floor, and roof. In the process, the initial shock wave, followed by a train of reflected waves, pass through the vent hole to the atmosphere outside the cubicle. At the same time, gas pressures building up inside the cubicle vent through the same hole. This process produces a high-pressure transient jet at the hole similar to the muzzle-blast from a gun

[8]. Outside the cubicle, the gas jet expands near the vent hole in a region commonly referred to as the "bottle" [8]. For the case of a gun, the high pressure gases suddenly vent at the moment the projectile leaves the muzzle and the bottle is bounded by shock waves oblique and normal to the axis of the vent hole [8]. Beyond the bottle, a primary shock wave envelopes the gas jet, expands in size, and at some distance from the vent hole smooths out into a nearly spherical shock wave [8]. Surrounding the bottle is a highly turbulent region where hot gas mixes with the outside air to form a strong annular vortex called the "smoke ring"[8]. This smoke ring was very pronounced and clearly visible from explosions in cubicle S4WPR.

A baffle orifice or muzzle brake attached to the muzzle of a gun has proven effective in reducing the pressures near the breech where operating personnel are stationed [8]. The muzzle brake interferes with the free expansion of the gas jet, thereby changing the shape of the shock front and distribution of strength along its front [8]. The merits of a muzzle brake attached to small vent openings in cubicles deserves study. If a muzzle brake substantially reduces the pressures outside a cubicle, then the vent opening conceivably could be increased to reduce the duration of gas pressures inside the cubicle and, thereby, reduce the strength of cubicle required to contain the explosion. A muzzle brake on cubicles may prove effective, it seems, if the pressure-time history outside the cubicle depends on the intensity of the shock waves formed by the gas jet (or bottle) instead of the intensity of the detonation waves from the explosion.

The peak gas pressure in a cubicle (< 1,000 psi) is generally much lower than the barrel pressure in a gun (~ 50,000 psi), and the cubicle continuously vents the gas pressure while a gun's pressure is dumped very suddenly. Therefore, the shock waves associated with the bottle for a cubicle are probably of much lower intensity than those from a muzzle blast. In any case, the entire process of detonation and gas venting produces a train of shock waves which travel away from the cubicle and attenuate with distance. With increasing distance, the rear waves in the train, traveling at a higher velocity, tend to catch up and merge with the initial shock wave. At any point outside the cubicle, the pressure-time history (Figures A-5 through A-10) has the characteristics of an unconfined explosion except that it contains a number of pronounced pressure spikes, particularly close to the cubicle. In all cases, the first pressure spike constitutes the largest pressure; the number of spikes decreases with distance, and, for a given charge weight, the number of spikes tends to decrease with increasing vent area.

The pi terms which could influence the peak positive pressure P_{so} outside a partially vented cubicle include the scaled charge density W/V, scaled vent area $A/V^{2/3}$, and the scaled distance to the charge $R/W^{1/3}$. These pi terms are scaled quantities and include all variables studied in the test program.

The pi terms can be expressed in other forms. For example, $A/V^{2/3}$ could be replaced by the scaled vent area $A/W^{2/3}$ since V and W are uniquely related by W/V.

A functional relationship between variables was found to predict measured values of P_{so} within the range of the experimental data. It was assumed that P_{so} is related to the three pi terms by a power series of the form

$$P_{so} = C_1 (A/V^{2/3})^{C_2} (W/V)^{C_3} (R/W^{1/3})^{C_4} \tag{6a}$$

The constants C_1, C_2, C_3, and C_4 in Equation 6a were determined from experimental data by using a least-squares curve fit in the logarithmic domain. Measured values of P_{so} for known values of $A/V^{2/3}$, W/V and $R/W^{1/3}$ (Table 3) were used to develop the curve fit. The resulting expression was

$$P_{so} = 290\left(\frac{A}{V^{2/3}}\right)^{0.401}\left(\frac{W}{V}\right)^{0.0025}\left(\frac{R}{W^{1/3}}\right)^{-1.496} \tag{6b}$$

The form of Equation 6b indicates that P_{so} is only slightly dependent on W/V, at least within the test range of charge densities ($0.063 \leq W/V \leq 0.375$). For example, $(W/V)^{0.0025}$ varies from 0.998 to 0.993 when W/V ranges from 0.375 to 0.063 lb/ft^3. Therefore, Equation 6b can be simplified, without introducing significant error, to

$$P_{so} = 290(A/V^{2/3})^{0.401}(R/W^{1/3})^{-1.496} \tag{6}$$

Equation 6 is compared with measured pressures in Figures 16 through 19 for each test value of $A/V^{2/3}$. The correlation coefficient for Equation 6 is 0.995 which is excellent. One standard deviation for the measured peak pressures about Equation 6 is 20.6%. Because Equation 6 is a curve fit to test data, it should only be applied to conditions where variables fall within the test range of individual pi terms or

$$0.063 < W/V < 0.375 \text{ lb/ft}^3$$

$$0.0198 < A/V^{2/3} < 1.000$$

$$1.59 < R/W^{1/3} < 63.0 \text{ ft/lb}^{1/3}$$

It is important to note that the pi terms $A/V^{2/3}$ and W/V were varied in the test program by fixing W and varying A and W. Equation 6 should be correlated with data from tests in which the spread in V is large for the same range of $A/V^{2/3}$ and W/V listed above. This can only be accomplished by testing full scale cubicles with large charge weights. Therefore, full scale cubicle tests are recommended in order to verify that Equation 6 applies to full scale conditions.

A common restriction imposed on the design of a cubicle is to limit the peak pressure P_{so} at some building or other point located in the near vicinity of the cubicle. The charge weight W is often fixed for the design. In this case, according to Equation 6, the designer can reduce P_{so} to a safe level either by increasing the distance R between the cubicle and building or by decreasing the scaled venting $A/V^{2/3}$. An analysis of the variables in Equation 6 indicates that P_{so} is more sensitive to a change in R than a change in $A/V^{2/3}$. For example, to decrease P_{so} by 50%, either R must be increased 58% or $A/V^{2/3}$ decreased 82.2%. The important point is that the designer can still "buy considerable distance" by reducing $A/V^{2/3}$.

Equation 6 is compared with experimental data from cubicles S4WPR and S4W in Figure 20. The dashed curve in Figure 20 is the relationship between peak pressure and scaled distance for an unconfined surface burst of composition B cylinders with a length-to-diameter ratio of 1.0. This surface burst curve is based on the experimental data shown in Figure 21 for the cylinder sitting on a steel plate and also for the cylinder located one diameter above the steel plate.

The position of the surface burst curve in Figure 20 relative to the lines for various values of $A/V^{2/3}$ is significant. For $R/W^{1/3} > 20$, the surface burst curve lies slightly below the line for $A/V^{2/3} = 1.00$ which corresponds to cubicle S4W, the 4-wall cubicle without a roof. In other words, explosions confined inside a 4-wall cubicle without a roof can produce pressures slightly greater than those from an unconfined surface burst at large scaled distances.

Equation 6 was derived from experimental data involving a cube-shaped cubicle and $0.019 < A/V^{2/3} < 1.0$. Caution should be exercised in applying Equation 6 to other conditions. For example, consider two extreme shapes for a 4-wall open-top box. If the box is tall and slender, $A/V^{2/3} < 1.0$ but the box geometry is not cube shaped. In the opinion of the authors, any error in predicted pressures from Equation 6 is probably small for this case, provided the box has four walls. If the box is shallow, $A/V^{2/3} > 1.0$; Equation 6 would predict infinite pressures as the box geometry approaches a flat plate ($A/V^{2/3} >> 1.0$). Obviously, leakage pressures cannot substantially exceed those from a unconfined surface burst, regardless of the magnitude of $A/V^{2/3}$. Hence, in the opinion of the authors, the error in predicted pressures from Equation 6 could be large if $A/V^{2/3} > 1$. To accommodate this anomaly, predicted pressures outside 4-wall boxes should never be allowed to exceed that indicated by the surface burst curve shown in Figure 20, regardless of the pressure indicated by Equation 6.

Equation 6 was used to construct the design chart shown in Figure 22. The chart is useful in selecting the degree of venting needed to limit leakage pressures any distance outside a 4-wall cubicle to some safe level. A sample problem and solution which serves to illustrate the use of the chart follows.

Problem. It is necessary to protect a frangible building located 100 feet from a 4-wall cubicle containing 1,000 pounds of composition B explosive. The building can safely resist a peak positive pressure no greater than 5 psi. Operations inside the cubicle require 200 square feet of floor space and walls 10 feet high. What vent area is needed in the roof of the cubicle?

Solution. Given W = 1,000 pounds, R = 100 feet, P_{so} = 5 psi and V = 200 x 10 = 2,000 ft^3; therefore, $R/W^{1/3}$ = 10. Entering Figure 22 with $R/W^{1/3}$ = 10 and P_{so} = 5, one finds the required $A/V^{2/3}$ = 0.22. Thus, the vent area required in the roof of the cubicle is $A = 0.22V^{2/3} = 0.22(2{,}000)^{2/3} \approx 34.9$ ft^2.

It should be emphasized that the chart in Figure 22 is based on composition B explosive, cylindrical charges, and cube-shaped cubicles with the charge at the geometric center of the cubicle. However, changes in charge shape, location, and composition should introduce only small errors in leakage pressures obtained from Figure 22.

It is important to note that Figure 22 and Equation 6 are for predicting the pressures outside a 4-wall cubicle on a horizontal plane located at the elevation of the vent area. If the horizontal plane of interest lies below the plane of interest (h > 0), leakage pressures at points located within several wall heights from the cubicle are less than those given by Figure 22 and the difference increases with W/V. A procedure is outlined in Appendix C for applying Figure 22 to cases where h > 0.

Peak Positive Impulse. Frequently, blast pressures outside a cubicle are very short in duration compared to the fundamental period of vibration of structures located in the near vicinity of the cubicle. In this case, the blast loading is applied very quickly as an impulse which simply imparts an initial velocity to the structure. Resulting peak deflections and the extent of structural damage depend on the peak positive impulse, i_s, of the blast loading. For this reason, i_s is an important load parameter in design.

The scaled peak positive impulse $i_s/W^{1/3}$ measured outside the 4-wall cubicles is plotted in Figure 23. Consistent with the trend found for peak pressures, $i_s/W^{1/3}$ decreases with increasing values of $R/W^{1/3}$ and decreasing values of A. A smooth curve is drawn through the data points associated with each value of A. For a fixed A, all data points fall within 10% of the smooth curve.

For a fixed A, the data points almost consistently fall above or below the curve depending on the value of W/V. Points representing the largest W/V fall below the curve while those representing the smallest W/V fall above the curve, except for the smallest vent area. For A = 0.072, the spread in data points about the curve is as great between points representing the same W/V as between points representing different W/V.

The curves shown in Figure 23 were used to construct the chart shown in Figure 24. The chart assumes that $AW^{1/3}/V$ adequately defines the position of the curves shown in Figure 23. The chart is useful for selecting the vent area needed to limit the peak positive impulse at any range outside a 4-wall cubicle. The chart probably yields reasonable values of $i_s/W^{1/3}$ within the range of the test data, that is, $0.072 < W/V < 0.289$ and $0.008 < AW^{1/3}/V < 0.721$. Figure 24 indicates that for large values of $AW^{1/3}/V$, $i_s/W^{1/3}$ is almost independent of $AW^{1/3}/V$ and approaches the value from an unconfined surface burst. As $AW^{1/3}/V$ decreases in value, $i_s/W^{1/3}$ becomes more sensitive to $AW^{1/3}/V$ until, for values of $AW^{1/3}/V < 0.02$, a given reduction in $AW^{1/3}/V$ produces almost an identical percentage reduction in $i_s/W^{1/3}$.

The ratio A/V ranges from about 0.10 to 0.67 for prototype 4-wall cubicles without a roof. Therefore, if $64 < W < 8{,}000$ pounds, then $0.29 < AW^{1/3}/V < 1.3$ for a wide range of charge weights and cubicle sizes. It follows then from Figure 24 that, except at very close-in ranges ($R/W^{1/3}$ less than about 10), the peak positive impulse outside 4-wall cubicles without a roof is about the same as that from an unconfined surface burst. In other words, a 4-wall cubicle without a roof will not significantly reduce the peak positive impulse outside the cubicle, except for combinations of $R/W^{1/3} < 10$ and $W < 64$ pounds.

The following problem and its solution serve to illustrate the use of the chart shown in Figure 24.

Problem. It is necessary to protect the roof slab of a building located 300 feet from a 4-wall cubicle containing 3,400 pounds of composition B explosive. Structural calculations indicate the roof slab is impulse sensitive (t_o/T_n is very small) and can resist an impulse load no greater than 30 psi-msec. The floor area of the cubicle is 200 square feet, and the walls are 10 feet high. What vent area is needed in the roof of the cubicle?

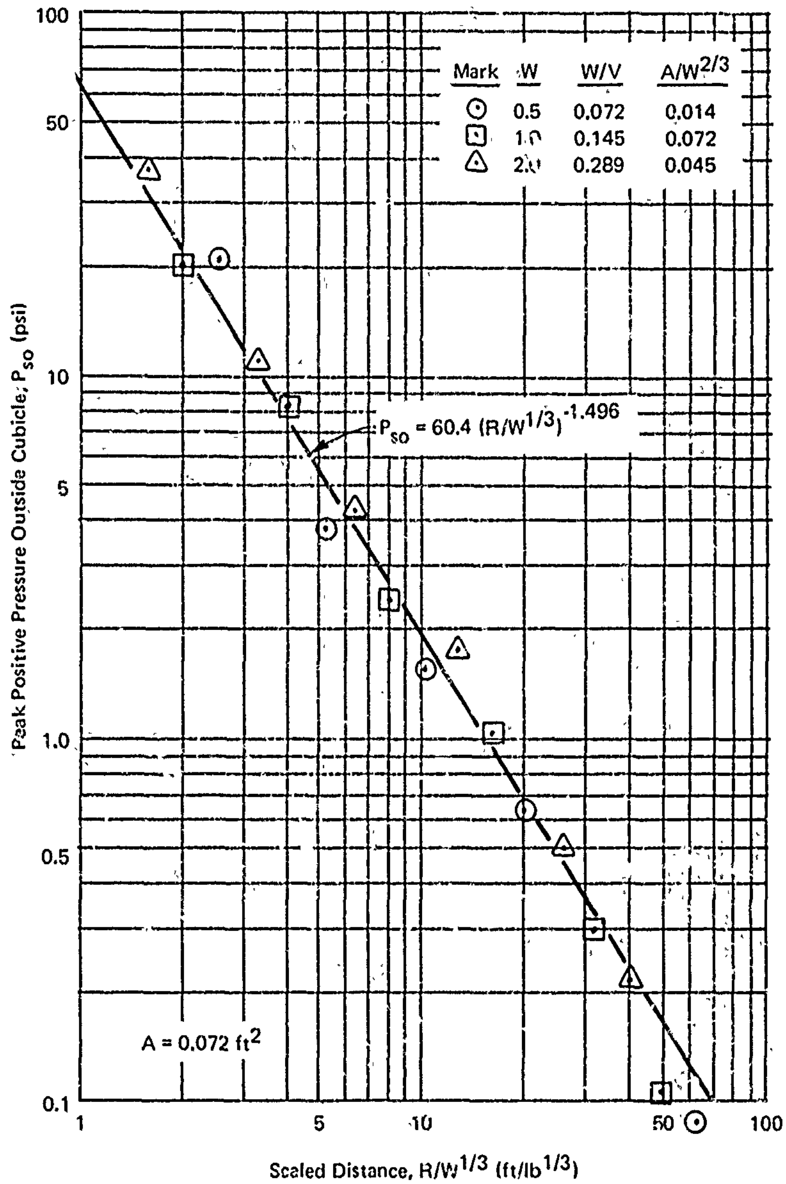


Figure 16. Peak positive pressure outside cubicle S4WPR versus scaled distance for $A/V^{2/3} = 0.020$.

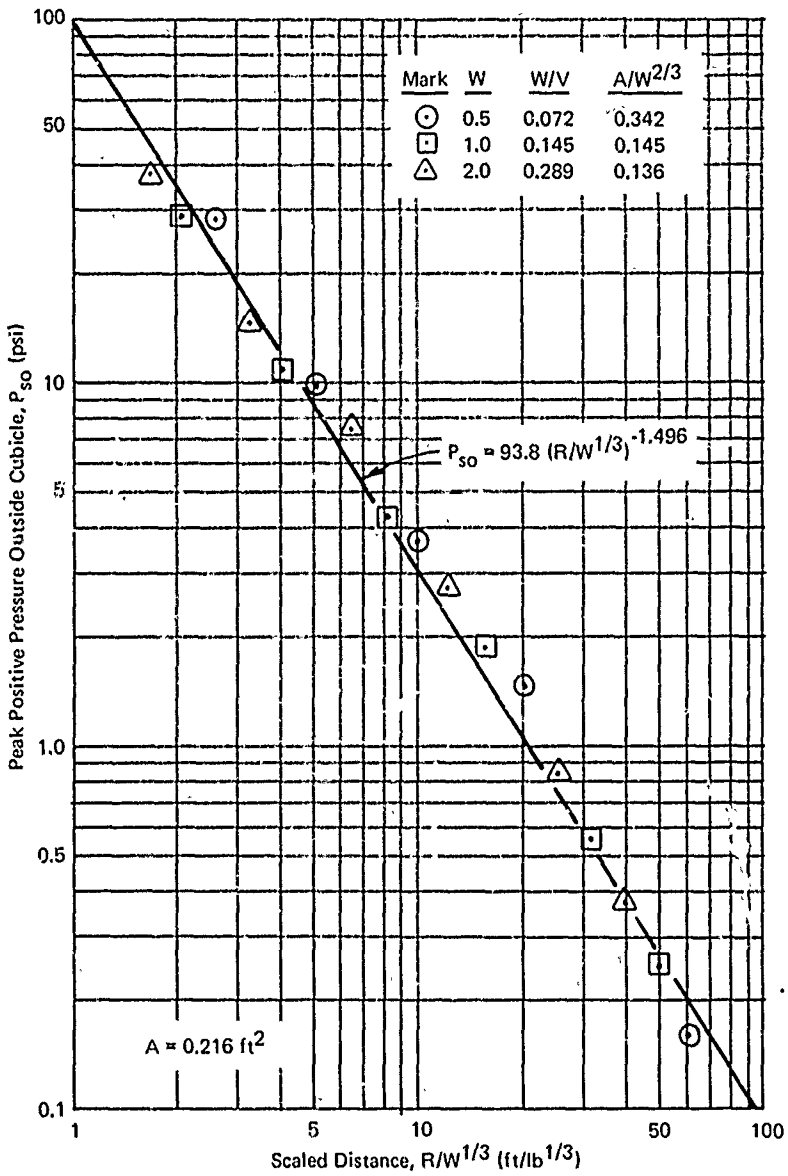


Figure 17. Peak positive pressure outside cubicle S4WPR versus scaled distance for $A/V^{2/3} = 0.060$.

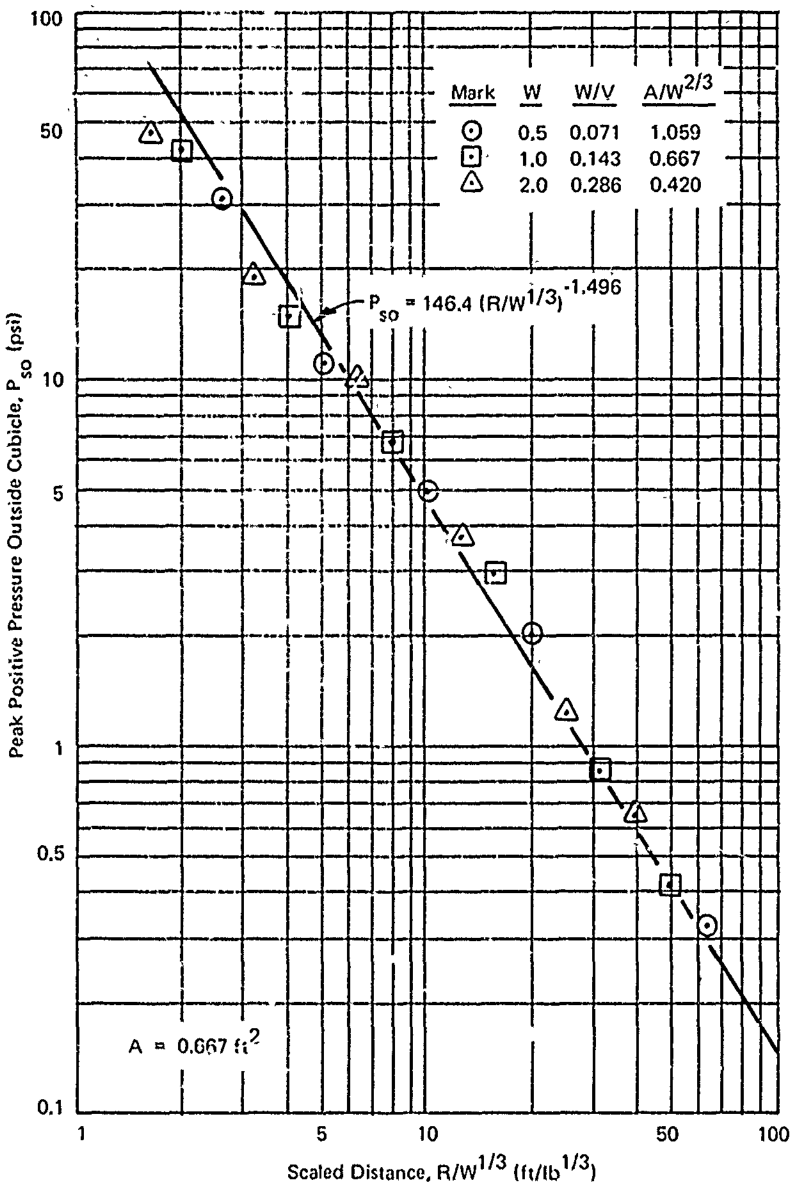


Figure 18. Peak positive pressure outside cubicle S4WPR versus scaled distance for $A/V^{2/3} = 0.182$.

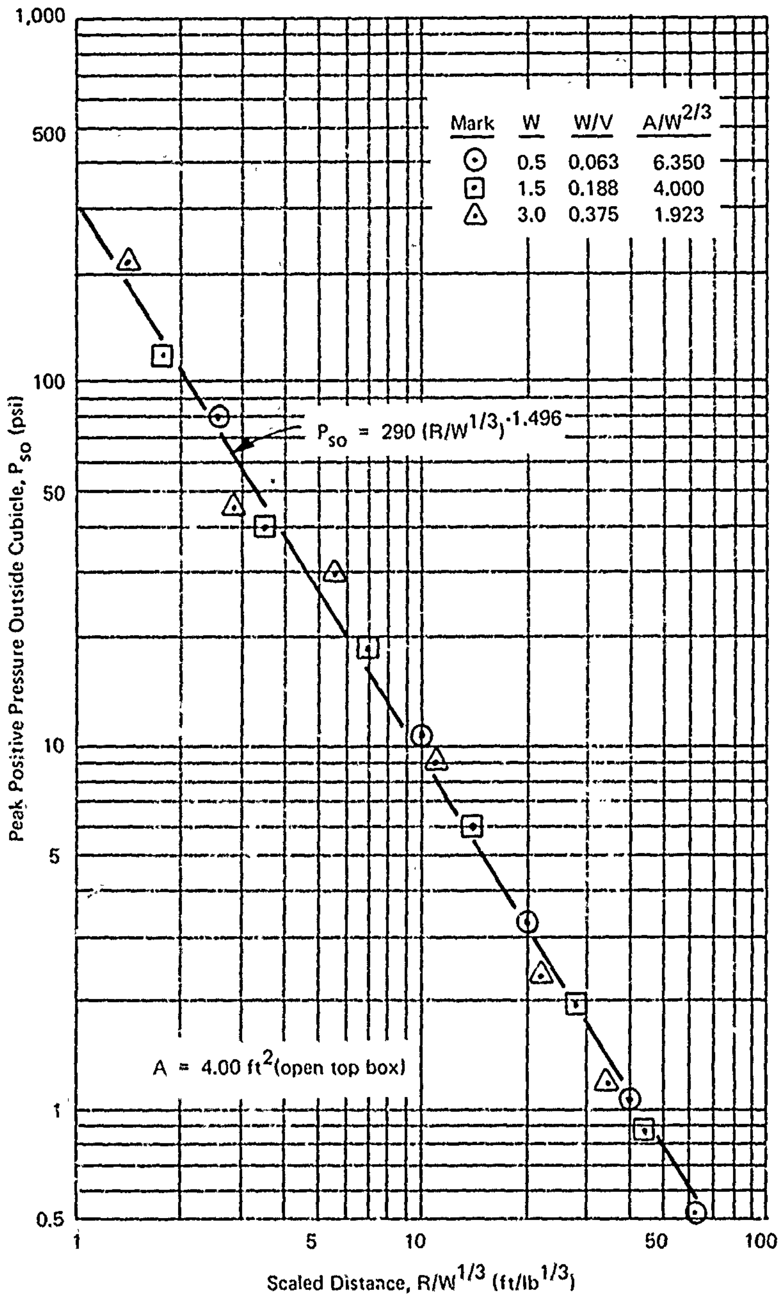


Figure 19. Peak positive pressure outside cubicle S4W versus $A/V^{2/3} = 1.0$.

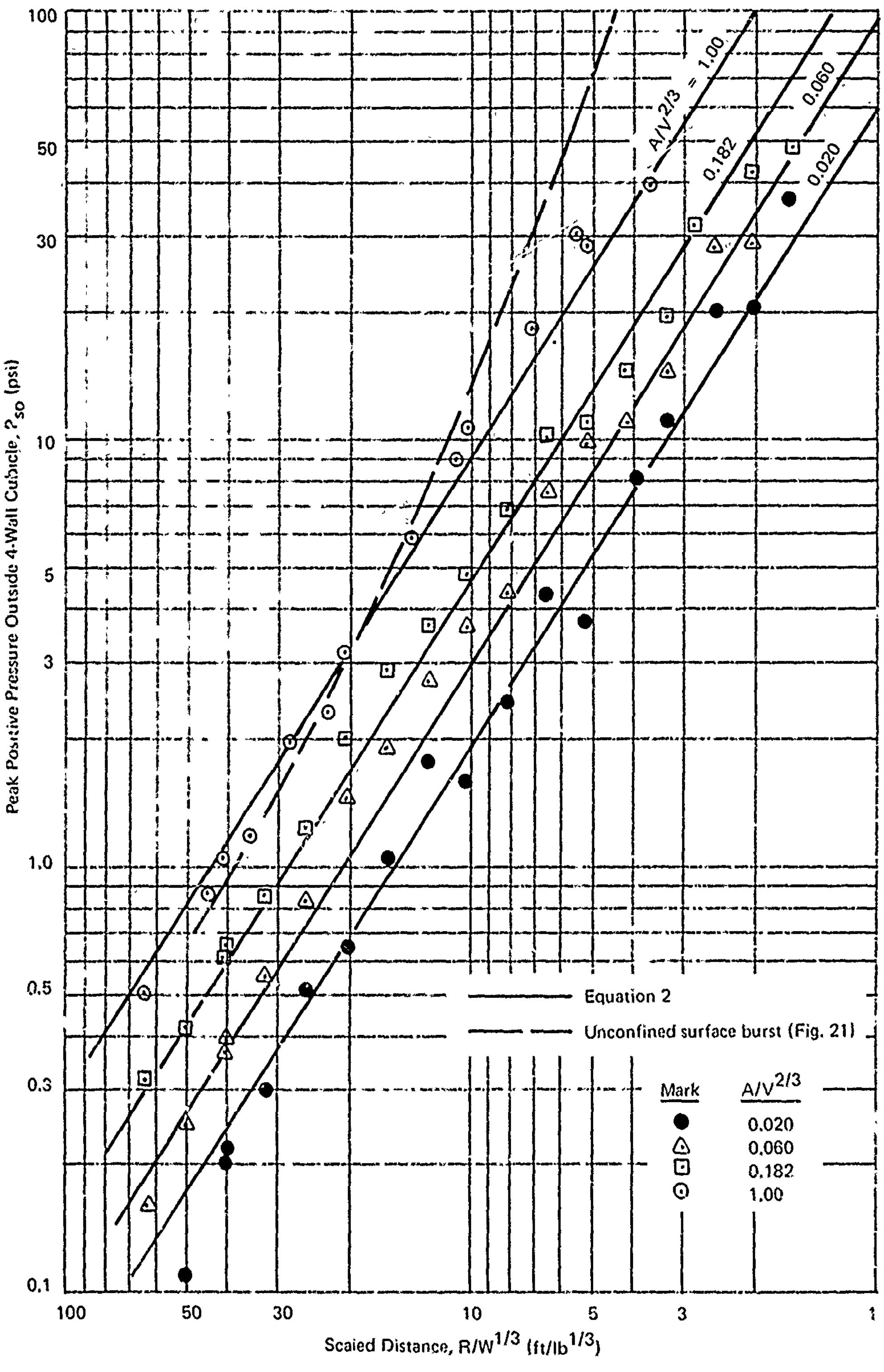


Figure 20. Comparison between measured and predicted peak positive pressures outside 4-wall cubicles.

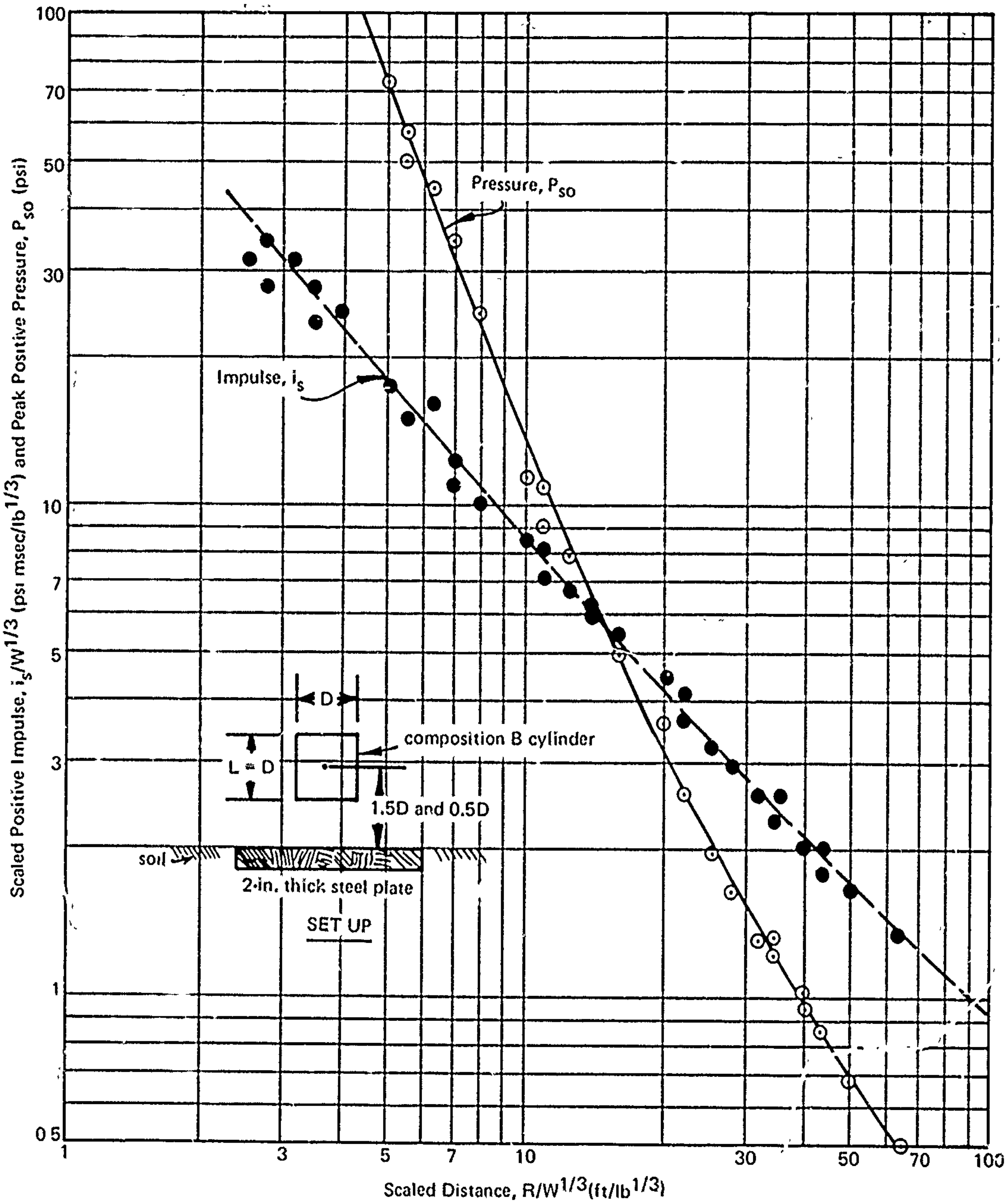


Figure 21. Positive pressure and impulse scaled distance from unconfined surface burst of composition B cylinder.

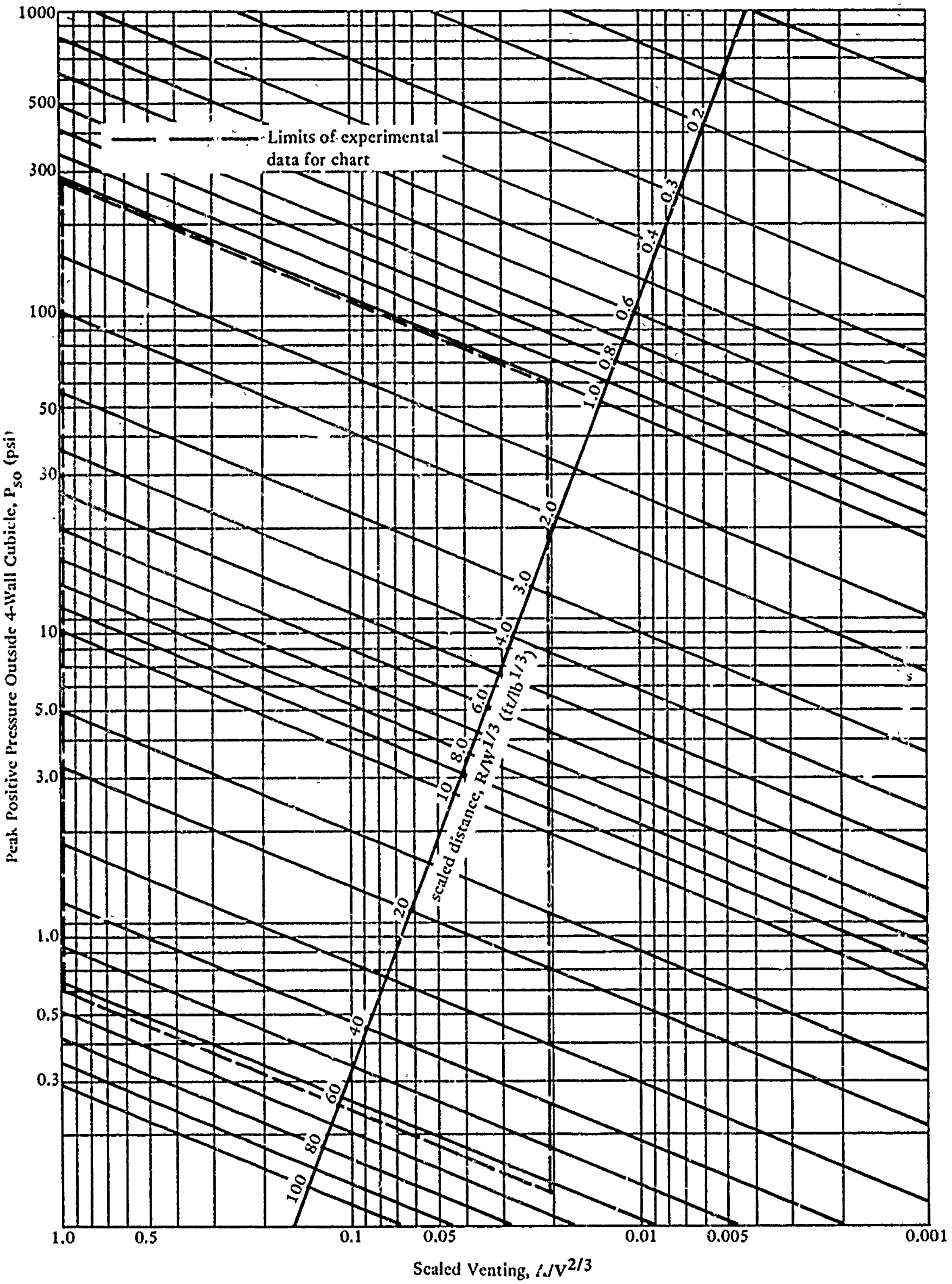


Figure 22. Design chart for vent area required to limit pressures at any range outside a 4-wall cubicle.

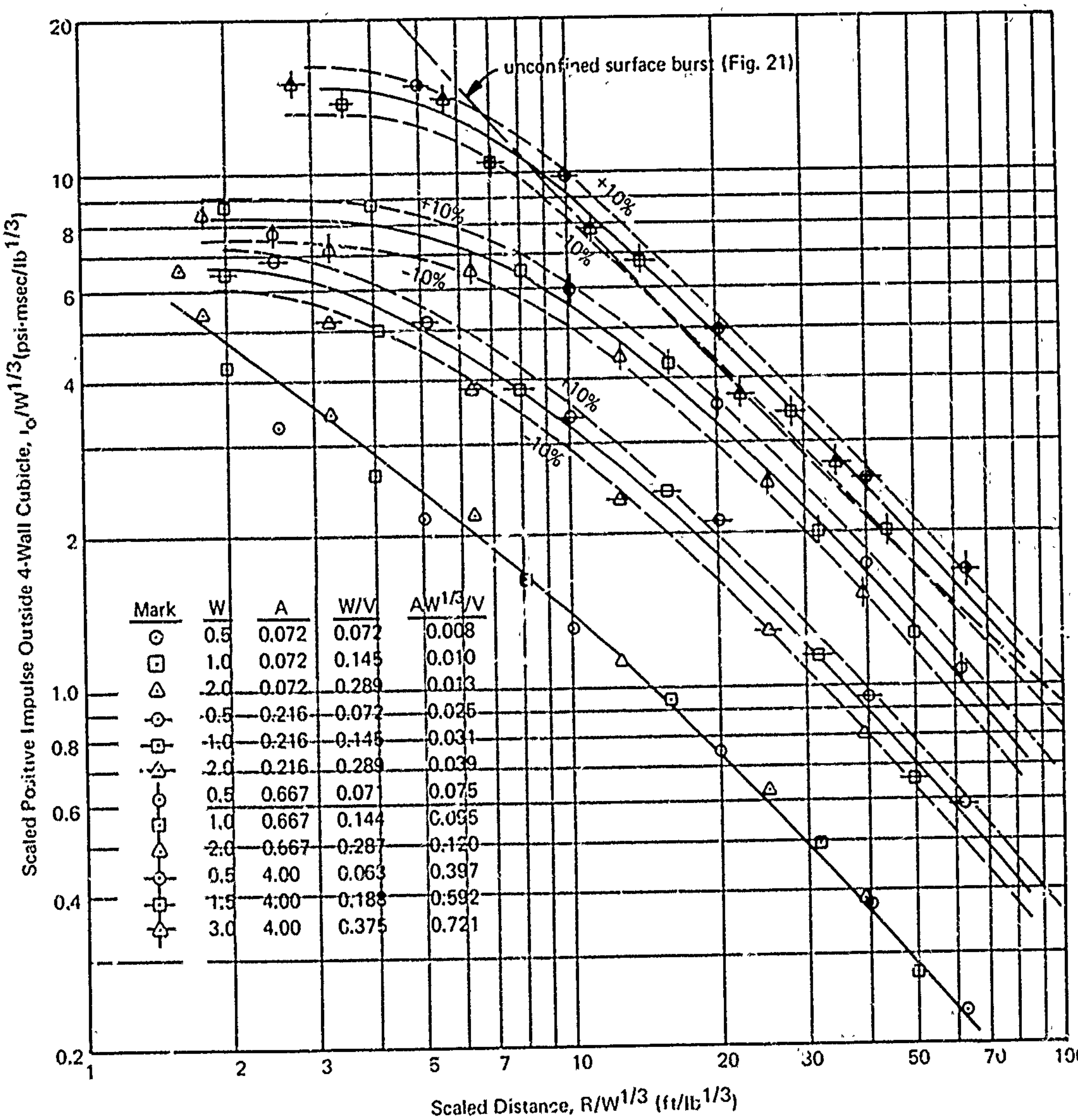


Figure 23. Scaled total positive impulse outside 4-wall cubicles versus scaled distance for A = 0.072, 0.216, 0.667, and 4.00 ft^2.

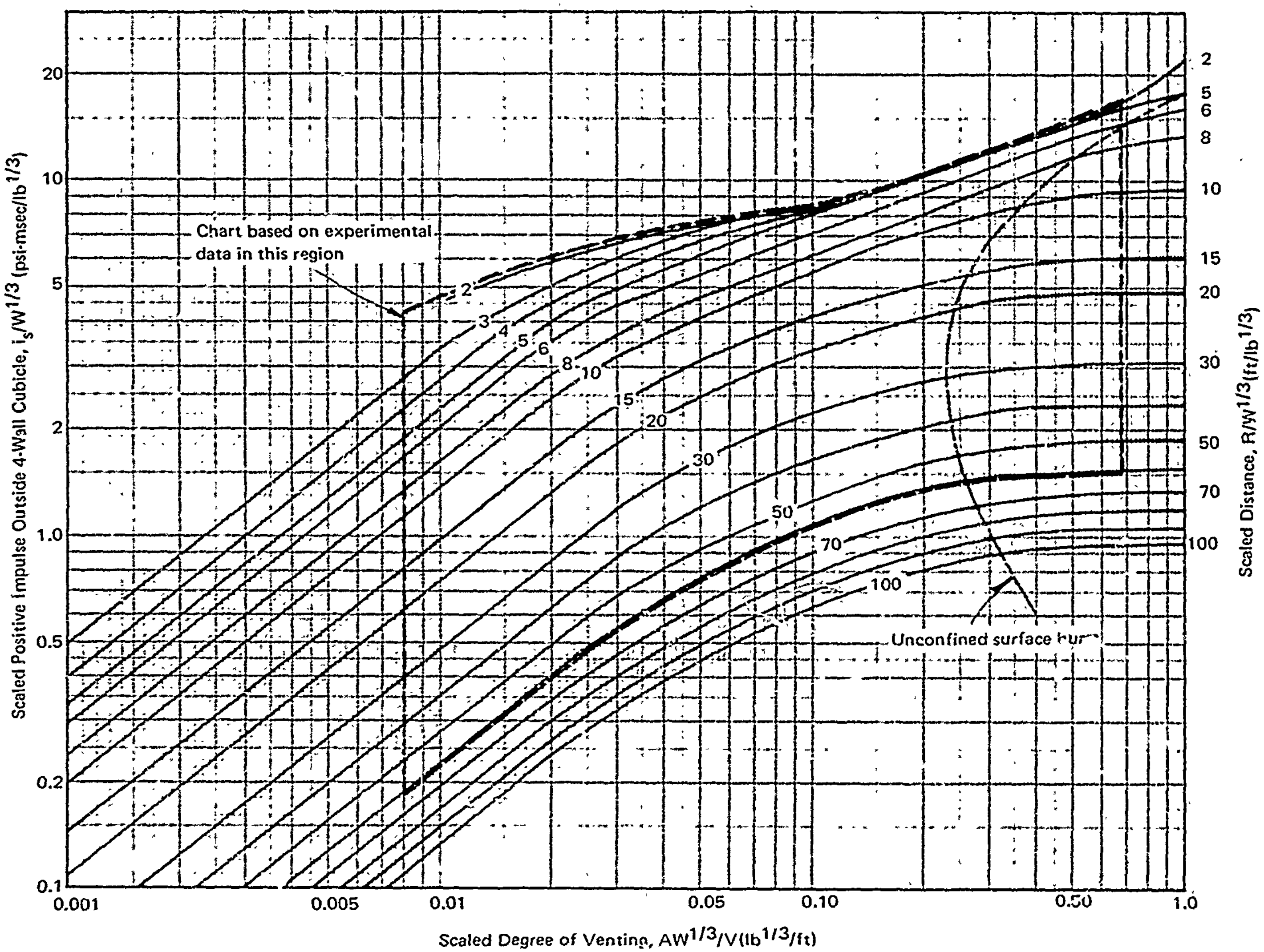
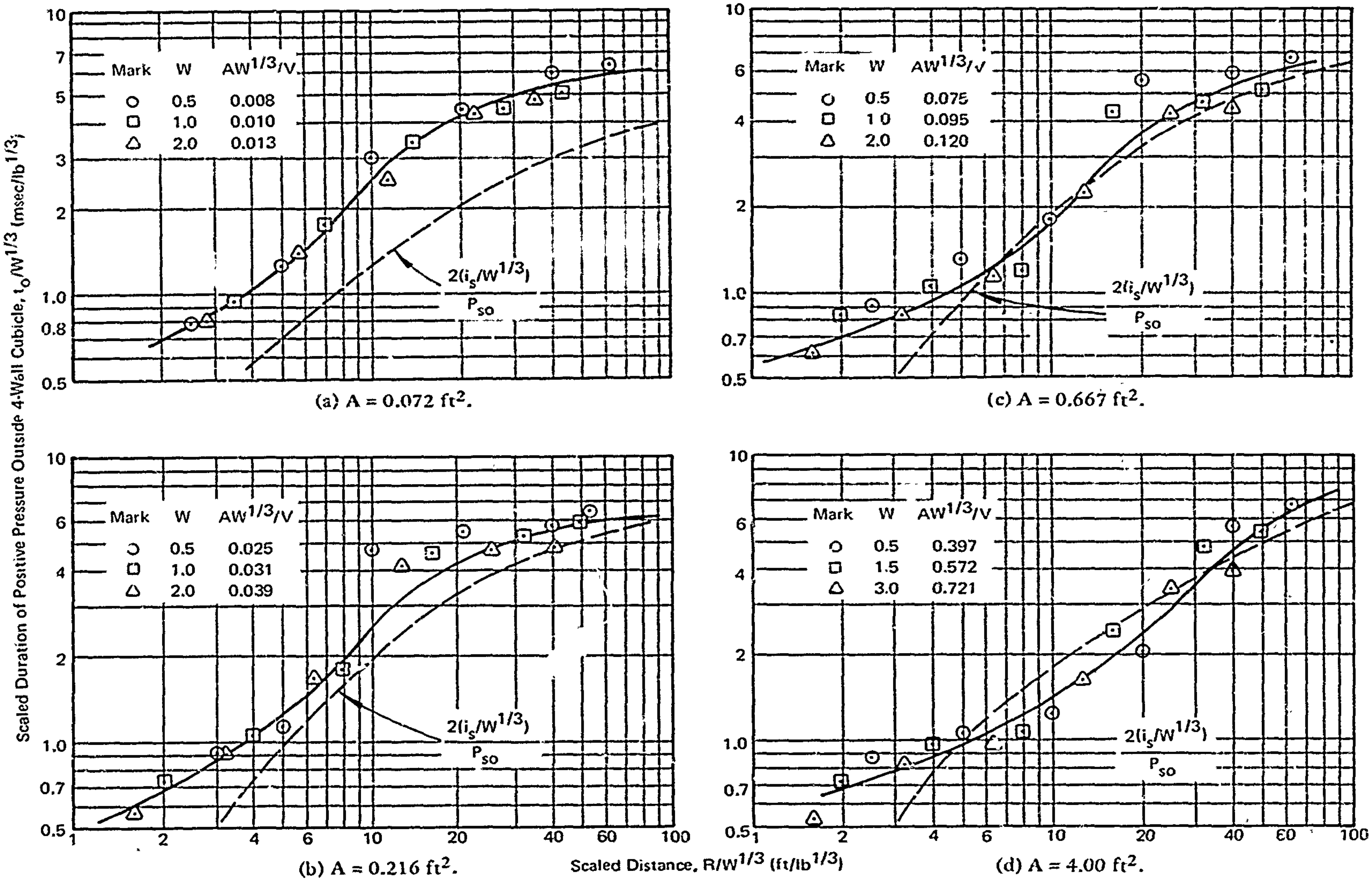


Figure 24. Design chart for vent area required to limit positive impulse at any range outside a 4-wall cubicle.



(a) $A = 0.072\ ft^2$.

(b) $A = 0.216\ ft^2$.

(c) $A = 0.667\ ft^2$.

(d) $A = 4.00\ ft^2$.

Figure 25. Scaled duration of positive pressure outside 4-wall cubicle versus scaled distance for various values of A.

Solution. Given W = 3,400 pounds, R = 300 feet, i_s = 30 psi-msec and V = 200 x 10 = 2,000 ft^3. Therefore, $R/W^{1/3}$ = 300/15 = 20 $ft/lb^{1/3}$ and $i_s/W^{1/3}$ = 30/15 = 2 psi-msec/$lb^{1/3}$. Entering Figure 24 with $R/W^{1/3}$ = 20 and $i_s/W^{1/3}$ = 2, one finds the required $AW^{1/3}/V$ = 0.035 $lb^{1/3}$/ft. Therefore, the required vent area in the roof of the cubicle is A = 0.035 $V/W^{1/3}$ = 0.035 x 2,000/15 = 4.7 ft^2.

Duration of Positive Pressure. The actual pressure-time pulse from an explosion is described by a peak pressure which decays exponentially with time. But most theoretical procedures for predicting the dynamic response of structures are based on a triangular pressure-time pulse. Consequently, for design purposes, the actual pressure pulse is approximated by an equivalent triangular pressure-time pulse [1]. The duration of the actual pulse is replaced by a fictitious duration t'_0, such that the peak pressure P_{so} and total impulse i_s of the actual and equivalent pulses are identical [1].

$$t'_0/W^{1/3} = 2\left(i_s/W^{1/3}\right)/P_{so} \qquad (7)$$

Equation 7 is compared in Figure 25 with values of $t_0/W^{1/3}$ measured outside each of the 4-wall cubicles. Equation 7 was evaluated using values of $i_s/W^{1/3}$ and P_{so} given by the charts in Figures 24 and 22, respectively. A smooth curve through the data points is an s-shaped curve, characteristic of an unconfined surface burst. For each value of $AW^{1/3}/V$, the measured and computed scaled durations are in fair agreement, except for $R/W^{1/3} < 5$ and the smallest degree of venting. For $AW^{1/3}/V$ = 0.010, Equation 7 underestimates $t_0/W^{1/3}$ by a factor of about 2 over the entire range of $R/W^{1/3}$. This implies that the exponential decay in actual pressure pulse is much greater for small degrees of venting and small scaled distances.

Definition of Partially Vented Explosion

It was shown that gas pressures develop from partially vented explosions in cubicles. This gas-pressure pulse can be far more damaging than the shock pulse, depending on the duration of the gas pulse t_g relative to the duration of the shock pulse t_0. If $t_g/t_0 < 1$, the explosion is classified as a fully vented explosion and the gas pulse, if any, can be neglected in the design of the cubicle. For $t_g/t_0 > 1$, the explosion is classified as a partially vented explosion and both the gas and shock pulses must be considered in the design of the cubicle. In the latter case, the importance of the gas pulse increases with t_g/t_0 until at some large value of t_g/t_0, the shock pulse can be neglected since its energy is insignificant compared to that in the gas pulse. Therefore, it is useful in the design to delineate between a fully and partially vented explosion to aid the designer in determining if the gas pulse must be considered in the design of the cubicle.

It was illustrated in Figure 11 that the region corresponding to t_g/t_0 = 1 is bounded by the dimensionless parameter $A/V^{2/3}$ which is independent of the physical size of the cubicle and the charge. According to Figure 11, t_g/t_0 = 1 corresponds to a value of $A/V^{2/3}$ somewhere between 0.21 and 0.60, at least for the range of cubicles tested. To be conservative, it is recommended for design that a cubicle be considered partially vented if $A/V^{2/3} < 0.60$. This criterion implies that 3-wall cubicles with and without a roof and 4-wall cubicles without a roof are fully vented cubicles.

ANALYSIS OF FULLY VENTED EXPLOSIONS

An explosion is fully vented if $A/V^{2/3} > 0.60$, according to criteria proposed in the previous section. Within the practical range of aspect ratios, 3-wall cubicles with or without a roof satisfy this criterion. Reference 1 contains charts for predicting the pressure loading inside 3-wall cubicles. Therefore, the following analysis is limited to the blast environment outside 3-wall cubicles containing fully vented explosions.

Consider a charge located at the geometric center of a 3-wall cubicle. Detonation of the charge generates a shock wave which expands and travels outward from the explosion. The detonation wave strikes the nearest wall, then the farthest wall, and reflects back and forth between the walls and floor. In the process, the detonation wave, and an erratic train of reflected waves, escape to the outside of the cubicle by passing unobstructed through the open front and roof and by spilling over the top of the sidewalls and backwalls and around the vertical edge of the sidewalls.

Outside the open front the unobstructed detonation wave develops a peak positive pressure corresponding to an unconfined surface burst. But a short distance from the open wall, the reflected waves, traveling at a higher velocity, overtake and merge with the detonation wave. The merging process reinforces the shock front, causing the peak positive pressure and impulse to be greater now than those from an unconfined surface burst at all points beyond some critical distance from the open front. The critical distance will depend on the charge weight and its distance from the backwall. If the charge is large enough or close enough to the backwall, the critical distance will be located inside the cubicle. In any case, at essentially all points outside the open front, the peak pressure and impulse exceed those from an unconfined surface burst. The pressure-time pulse contains multiple pressure spikes caused by trailing reflected waves which have not yet overtaken the shock front. With increasing distance, more trailing waves catch up until at large-scaled distances the pressure pulse is characteristic of an unconfined surface burst.

Behind the sidewalls and backwalls, the train of shock waves spilling over and around the free edges of the back and sidewalls form a highly turbulent vortex at the free edges of the walls. At first the vortex is small but rapidly grows in size with time. The vortex apparently distorts the shock front enough to substantially decrease the peak positive pressure and impulse close to the cubicle. In fact, the peak pressure and impulse are reduced to a level much less than those from an unconfined surface burst.

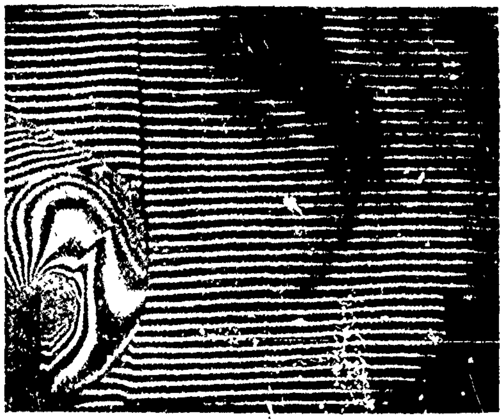
Evidence that a vortex indeed forms and grows to considerable size behind a barrier wall is shown in a study by G. Teel who recorded the shock wave patterns in aircraft revetments [9]. Teel placed small-scaled models of walls in a shock tube and, using smoke columns and a camera, recorded the flow patterns over a wall exposed to a shock wave. Typical flow patterns which show the growth of the vortex are shown in Figure 26. Note that the vortex grew in size to a diameter about equal to the wall height, drifted away from the wall to a point located about 0.5 to 1.5 wall heights away, and was still at its maximum size 0.92 msec after the wave first struck the wall. It seems reasonable to hypothesize that the size of this vortex and the extent of its influence on peak pressure and impulse depend primarily on the energy in the detonation wave at the wall and the size of the wall. In any case, out to some critical scaled distance from the walls, the peak positive pressure and impulse are less than those from an unconfined surface burst. Beyond this critical scaled distance, the peak positive pressure and impulse decrease with increasing scaled distance but may exceed those from an unconfined surface burst because of reflected waves that reinforce the shock front.

Consider a 3-wall cubicle with the charge located at its geometric center. The scaled area of the sidewall is $L_sH/W^{2/3}$ and the scaled distance from the charge to the sidewall is $L_b/2W^{1/3}$. The product of these terms is $(L_sH/W^{2/3})(L_b/2W^{1/3}) = 0.5(W/V)^{-1}$. Now the detonation wave and succeeding reflected waves in escaping from the cubicle view the wall as an obstruction which, according to the above formulation, increases as W/V decreases. Therefore, the hypothesis is made that the blast environment outside a 3-wall cubicle is dependent on W/V, a scalable parameter that can be used to relate the test data to a full scale condition.

Peak Pressure Outside 3-Wall Cubicles

3-Wall Cubicle Without Roof. Peak pressures behind the sidewalls, backwalls, and open front walls of cubicles S3W and L3W are plotted as a function of scaled distance in Figures 27 through 31. The solid curve in each figure is the best-fit curve of the data. The relative position of the unconfined surface burst curve in each figure illustrates the effect of confining the charge inside a cubicle. The appropriate curve from Figure 4-63 of Reference 1 (TM5-1300) is also shown to compare results obtained from full-scale tests of rectangular-shaped, 3-wall cubicles [2].

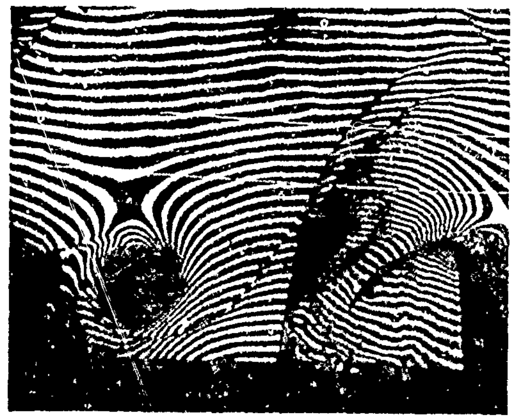
Behind the open front (Figure 27) there is no clear influence of cubicle geometry or W/V on the peak pressures at any scaled distance. Therefore, the best-fit curve applies to both cubicles and all values of W/V. Note that the solid curve falls above the surface burst curve and the TM5-1300 curve at all scaled distances. The latter difference may be attributed to the fact that the TM5-1300 curve is based on data from different charge shapes (stacked blocks and spheres) and larger values of W/V (0.28 to 0.62 lb/ft^3).



(a) T = 178 μsec.

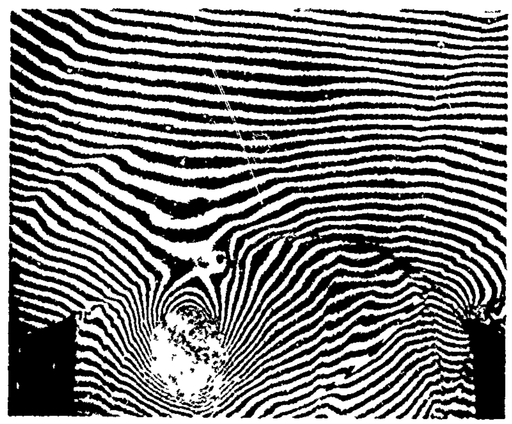
(b) T = 229 μsec.

(c) T = 402 μsec.



(d) T = 521 μsec.

(e) T = 583 μsec.



(f) T = 921 μsec.

Figure 26. Growth of the vortex behind a wall exposed to a shock wave [9].

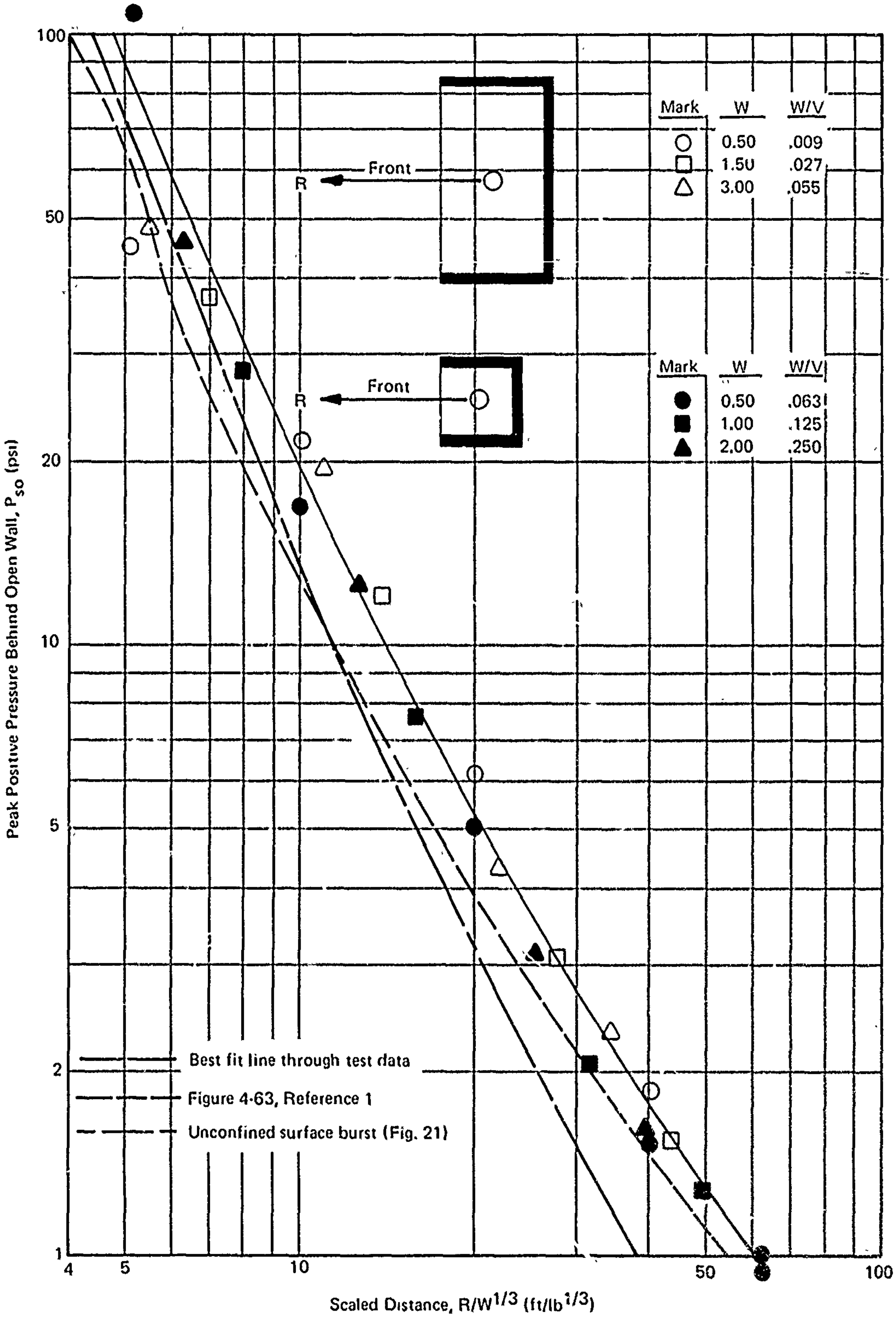


Figure 27. Peak positive pressure out the open front of 3-wall cubicles without a roof.

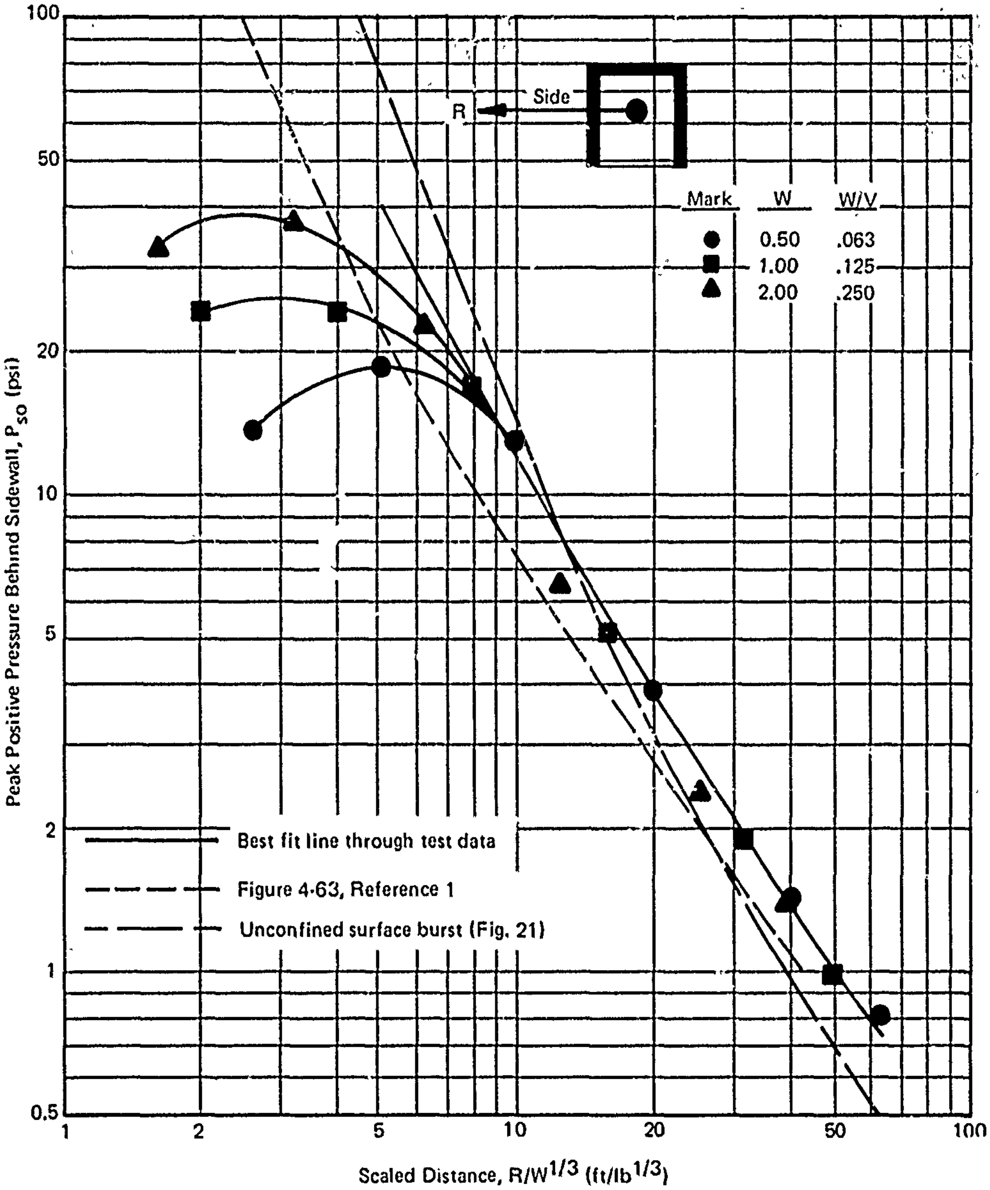


Figure 28. Peak positive pressure behind sidewall of small 3-wall cubicle without roof.

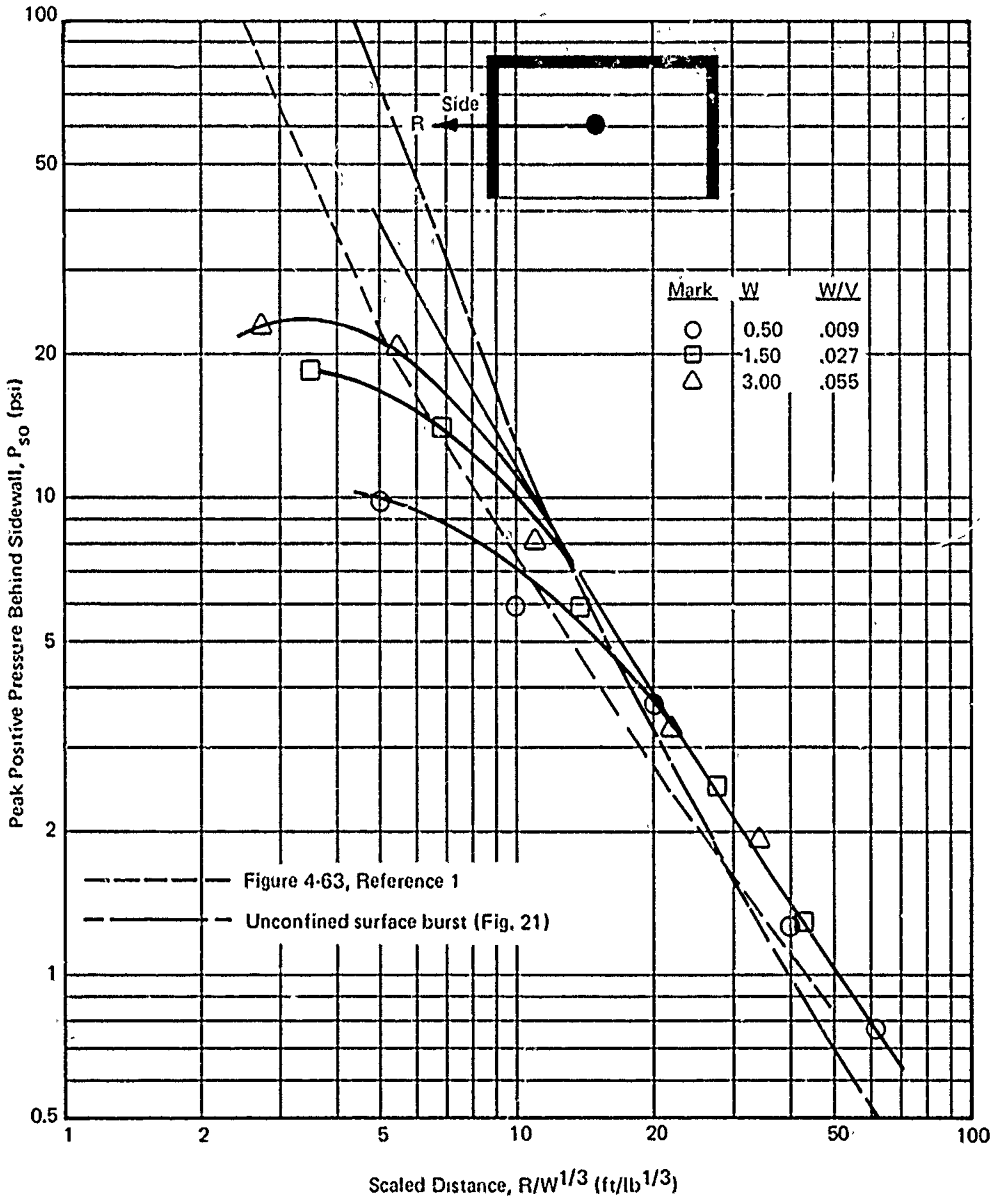


Figure 29. Peak positive pressure behind sidewall of large 3-wall cubicle without roof.

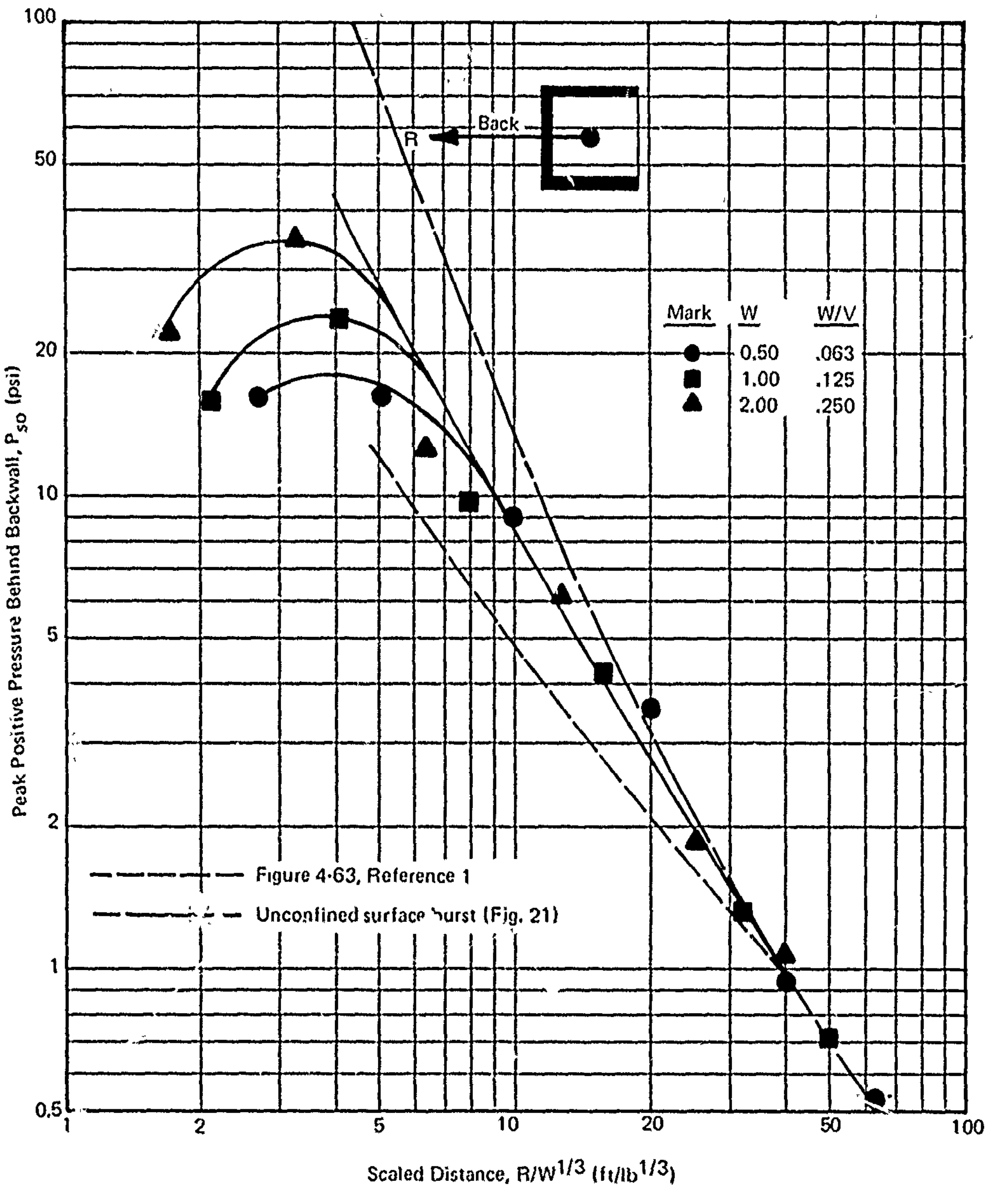


Figure 30. Peak positive pressure behind backwall of small 3-wall cubicle without roof.

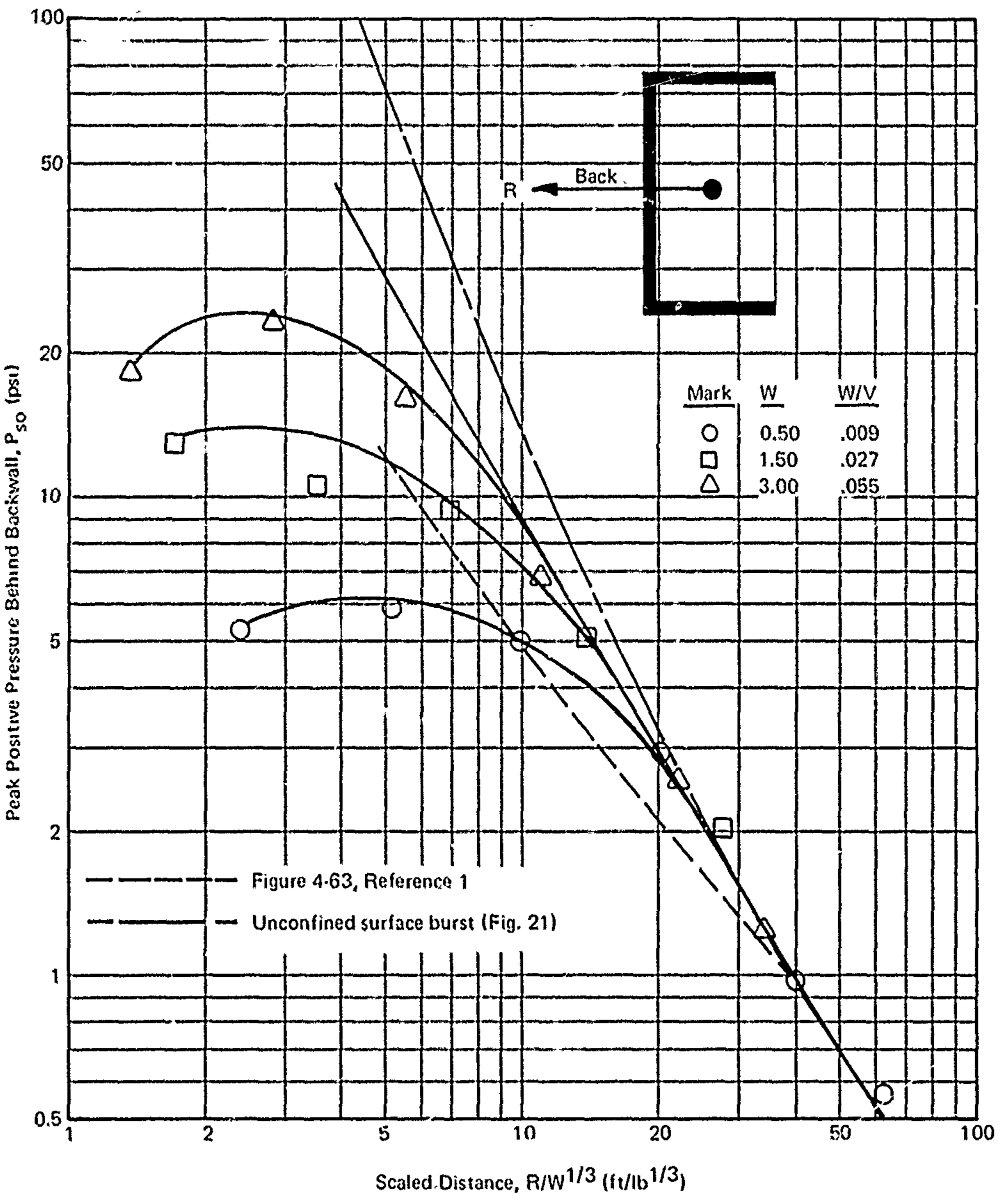


Figure 31. Peak positive pressure behind backwall of large 3-wall cubicle without roof.

Behind the sidewalls and backwalls (Figures 28 through 31) there is no clear influence of cubicle geometry or W/V on peak pressure at large scaled distances. Further, the best-fit curves are identical at far points behind similar walls of the cube- and rectangular-shaped cubicles. At these far ranges, the pressure curve rises with decreasing scaled distance. This portion of the curve is referred to as the envelope curve. With decreasing scaled distance, the pressure curve gradually bends away from the envelope curve, eventually peaks out, and then gradually begins to decline. The fact that the curve peaks out instead of continuously rising with decreasing $R/W^{1/3}$ is believed to be the effect of the vortex which forms behind the wall (see Figure 26). The peak in the pressure curve is defined as $(P_{so})_{max}$ and increases with W/V.

3-Wall Cubicle With Roof. Peak pressures outside a 3-wall cubicle with a nonfrangible roof are shown in Figures 32 through 36. At any scaled distance there is no clear influence of cubicle geometry or W/V on the peak pressures out the open front (Figure 32). Therefore, the best-fit curve applies to both cubicles and all values of W/V. Note that the curve falls above the surface burst curve for all values of $R/W^{1/3}$.

At large-scaled distances behind the sidewalls and backwall (Figures 33 through 36), there is no clear influence of cubicle geometry or W/V on peak pressure. The envelope curves are identical at far points behind similar walls of both the cube- and rectangular-shaped cubicles. With decreasing scaled distance, the pressure curve gradually bends away from the envelope curve, eventually peaks, and then begins to decline. The peak in the curves at a small scaled distance is attributed to the effects of the vortex which forms behind the wall (see Figure 26). The pressure at the peak in the curve $(P_{so})_{max}$ increases with W/V.

Design Curves for Peak Pressure

The envelope curves (from Figures 27 through 31) for the peak positive pressure behind the front, backwalls and sidewalls of the 3-wall cubicles without a roof are shown in Figure 37. Similar curves for the peak positive pressure outside 3-wall cubicles with a roof are shown in Figure 38. At all scaled distances, the peak pressure indicated by these envelope curves is greatest out the front, less behind the sidewalls, and least behind the backwall. The curves apply to both the cube- and rectangular-shaped cubicles.

From the curves for pressure behind cubicle walls in Figures 28 through 31 and 33 through 36, $(P_{so})_{max}$ is plotted as a function of W/V in Figure 39. $(P_{so})_{max}$ depends on direction, W/V, and cubicle geometry. However, only two curves are necessary to define the peak pressure adequately for the cubicle geometries tested. The peak pressure behind the backwall of the cubicles with a roof were the only pressures that were significantly lower. The pressures out the front wall are not dependent on W/V and are fully described in Figures 27 and 32.

The envelope curves in Figures 37 and 38 must be used in conjunction with Figure 39. In certain cases, P_{so} from Figure 37 will exceed $(P_{so})_{max}$ from Figure 39, especially for small values of $R/W^{1/3}$ or W/V. In these cases, $(P_{so})_{max}$ is the maximum peak pressure outside the cubicle.

The following problem and its solution illustrate the use of the design charts in Figures 37 through 39.

Problem. Design a 3-wall cube without a roof to contain 125 pounds of composition B explosive. The pressures anywhere behind the backwall and sidewalls must not exceed 15 psi. (a) What wall dimensions are required? (b) What will the peak pressure be behind the sidewall, backwall and front wall at a range of 200 ft?

Solution. (a) Given W = 125 pounds and $(P_{so})_{max}$ = 15 psi, from line A in Figure 39 the required W/V = 0.017 or V = 125/0.017 = 7,350 ft^3. For a cube, $L = V^{1/3} = (7{,}350)^{1/3} = 19.4$ ft. Therefore, the length and height of the sidewalls and backwall must be 19.4 feet. (b) Given R = 200 ft, W = 125 lbs and V = 7,350 ft^3. Therefore, $R/W^{1/3} = 200/(125)^{1/3} = 40$ and W/V = 0.017. From Figure 37, P_{so} = 1.0 psi behind the backwall, 1.5 psi behind the sidewall and 1.8 psi out the open front. From Figure 39, $(P_{so})_{max}$ = 15 psi. $(P_{so})_{max} > P_{so}$; and, therefore, values of P_{so} from Figure 37 are correct.

Duration of Positive Pressure

The positive duration t_0 of the real pressure-time pulse is seldom used for design. Instead,

structural response is commonly based on an equivalent triangular-shaped pulse having the same peak pressure P_{so} and impulse i_s, but a fictitious duration t_o' equal to $2i_s/P_{so}$. Therefore, detailed analysis of $t_o/W^{1/3}$ (listed in Tables 4 through 7) is not given here, but a correlation of the data indicates that: (1) $t_o/W^{1/3}$ increases with decreasing W/V, (2) the influence of W/V on $t_o/W^{1/3}$ diminishes with increasing $R/W^{1/3}$, and (3) at large scaled distances, the effect of W/V is negligible and $t_o/W^{1/3}$ approaches that from an unconfined surface burst.

Total Positive Impulse

Impulse data are tabulated in Tables 4 through 7 and discussed in Appendix B. Attempts to develop design curves, similar to those for peak pressure, from the scale model impulse data were unsuccessful. However, scaled relationships were derived that, for specific cases, will predict full scale results. These relationships are discussed and presented in Appendix B.

Effect of Roof on Exterior Blast Environment

The major benefit derived from adding a roof to a 3-wall cubicle is a 70 to 80% reduction in the peak pressures close-in behind the backwall (compare curves in Figure 39). The roof has no significant influence on maximum peak pressures behind the sidewalls (see curves in Figure 39). According to Figures 37 and 38, at large scaled distances the roof increases P_{so} out the open front and behind the sidewalls but has no significant effect on P_{so} behind the backwall.

Full-Scale Versus Small-Scale Cubicle Tests

In 1967 NOTS, China Lake, California, measured external leakage pressures from three explosions in a full-scale cubicle [2]. The cubicle was a 3-wall configuration with interior dimensions measuring 40 feet long, 20 feet wide, and 10 feet high. The explosive charges in tests 1 and 2 were 2,000- and 3,000-pound spheres of composition B, respectively. In test 3, the charge consisted of one hundred 50-pound blocks of TNT, or the equivalent of 4,420 pounds of composition B. In each test, the charge was located at the geometric center of the cubicle. Leakage pressures were measured on the ground surface along lines normal to the sidewalls, backwall and open front at points 90 to 1,100 feet from the center of the charge. Pressure data from these tests culminated in the design curves presented in Figure 4-63 of Reference 1.

Appropriate curves from Figure 4-63 are compared with similar curves from the CEL scale model tests in Figures 27 through 31. The NOTS curves (from full-scale tests) indicate peak pressures behind the sidewalls, and backwall and out the open front are less than those indicated by the CEL curves (from scale model tests), especially for $R/W^{1/3} < 30$. This difference is attributed to one or more of the following factors: (1) differences between tests in charge shape and range of W/V, (2) inaccuracies in scaling, (3) accuracy and interpretation of peak-pressure data, and (4) the estimate of the best-fit curve for the data. Regarding charge shape, the NOTS curves are based on spheres while the CEL curves are based on cylinders (L/D = 1). Tancreto and other investigators found that for the same scaled distance a cylinder produces higher peak pressures than a sphere, for $R/W^{1/3} < 20$ [10].

The NOTS curves show no peaking out of the pressure curve behind the backwall and sidewalls; leakage pressures increase continuously with decreasing scaled distance. The curves in Figures 37 and 39 indicate this would indeed be the case. For example, in the NOTS tests, $W/V > 0.25$ lb/ft^3 which according to Figure 39 (line A) would result in $(P_{so})_{max} \geq 43$ psi. In Figure 37, $P_{so} \geq 43$ psi behind the sidewalls and backwall corresponds to $R/W^{1/3} \leq 4$ ft/lb$^{1/3}$; but NOTS pressure transducers were never located closer than 6.2 ft/lb$^{1/3}$, so the phenomenon could never be detected from the NOTS data.

PROPOSED DESIGN CRITERIA

Criteria are outlined in Figures 40 and 41 for predicting the design loading in and around fully and partially vented cubicles. The criteria for the design loading inside fully vented cubicles are compatible with procedures outlined in Reference 1. Design charts are based on measurements at h = 0 for 4-wall cubicles and h = H for 3-wall cubicles. Appendix C outlines a method for estimating the exterior blast environment for other values of h.

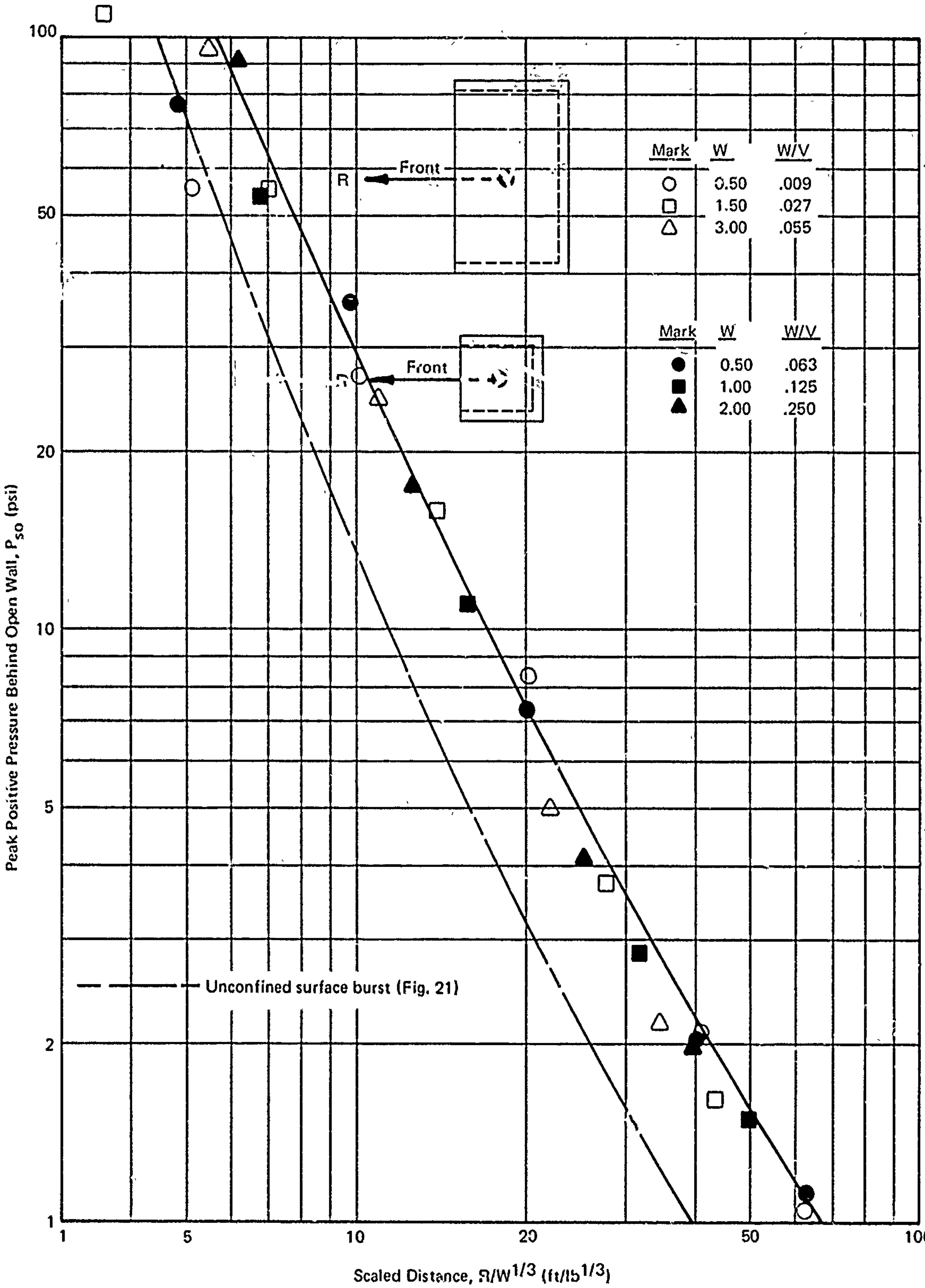


Figure 32. Peak positive pressure out the open front of 3-wall cubicles with roof.

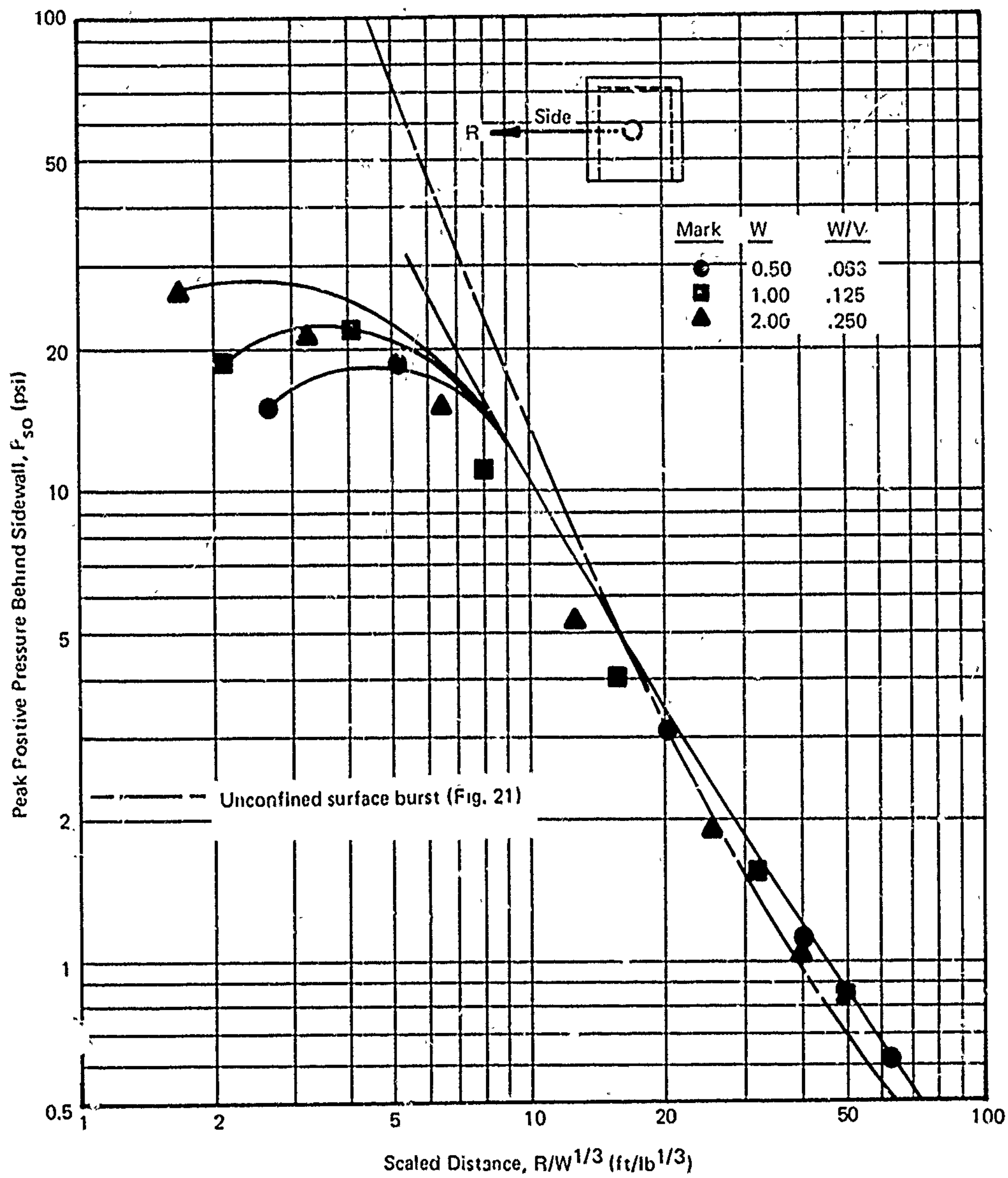


Figure 33. Peak positive pressure behind sidewall of small 3-wall cubicle with roof.

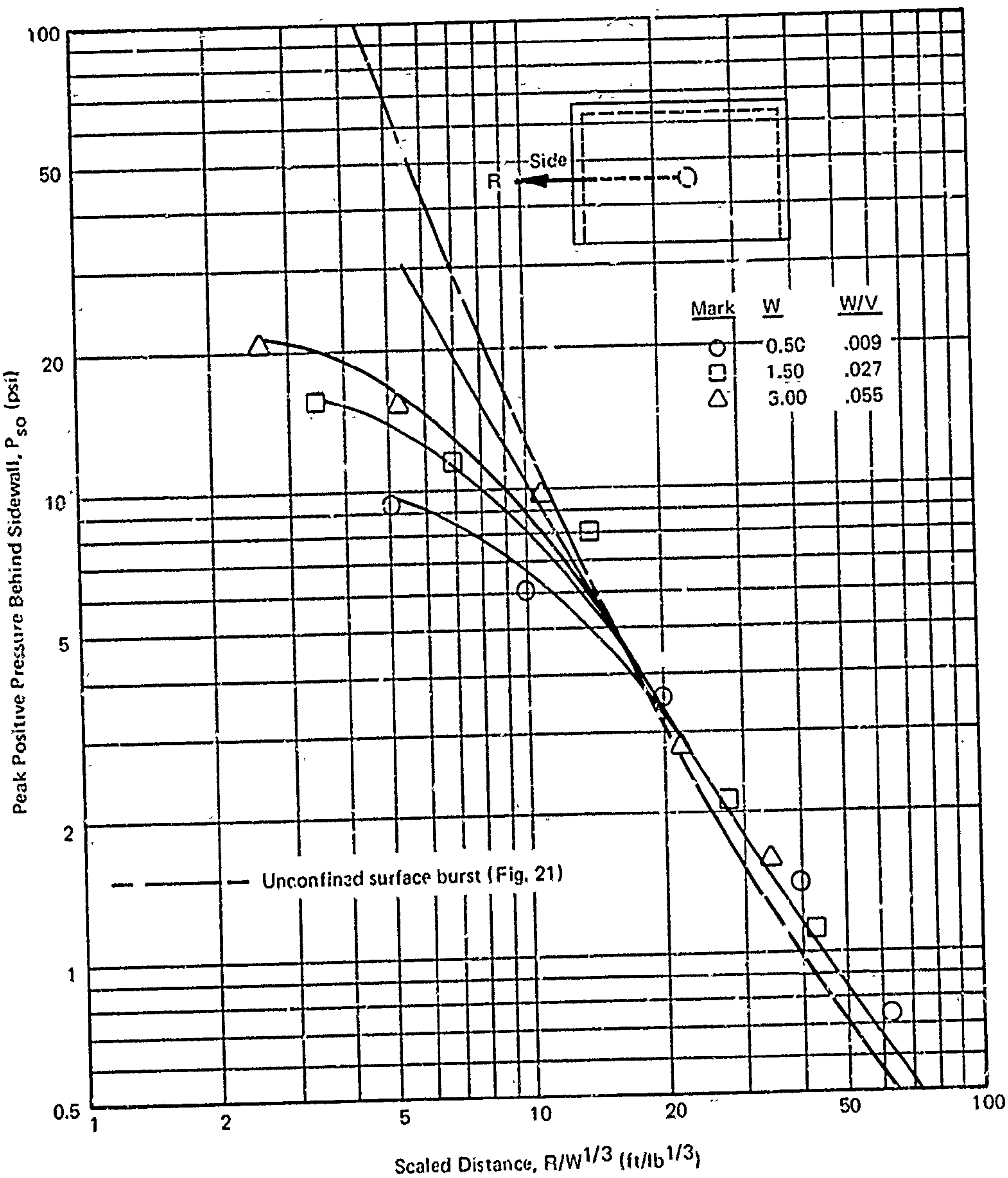


Figure 34. Peak positive pressure behind sidewall of large 3-wall cubicle with roof.

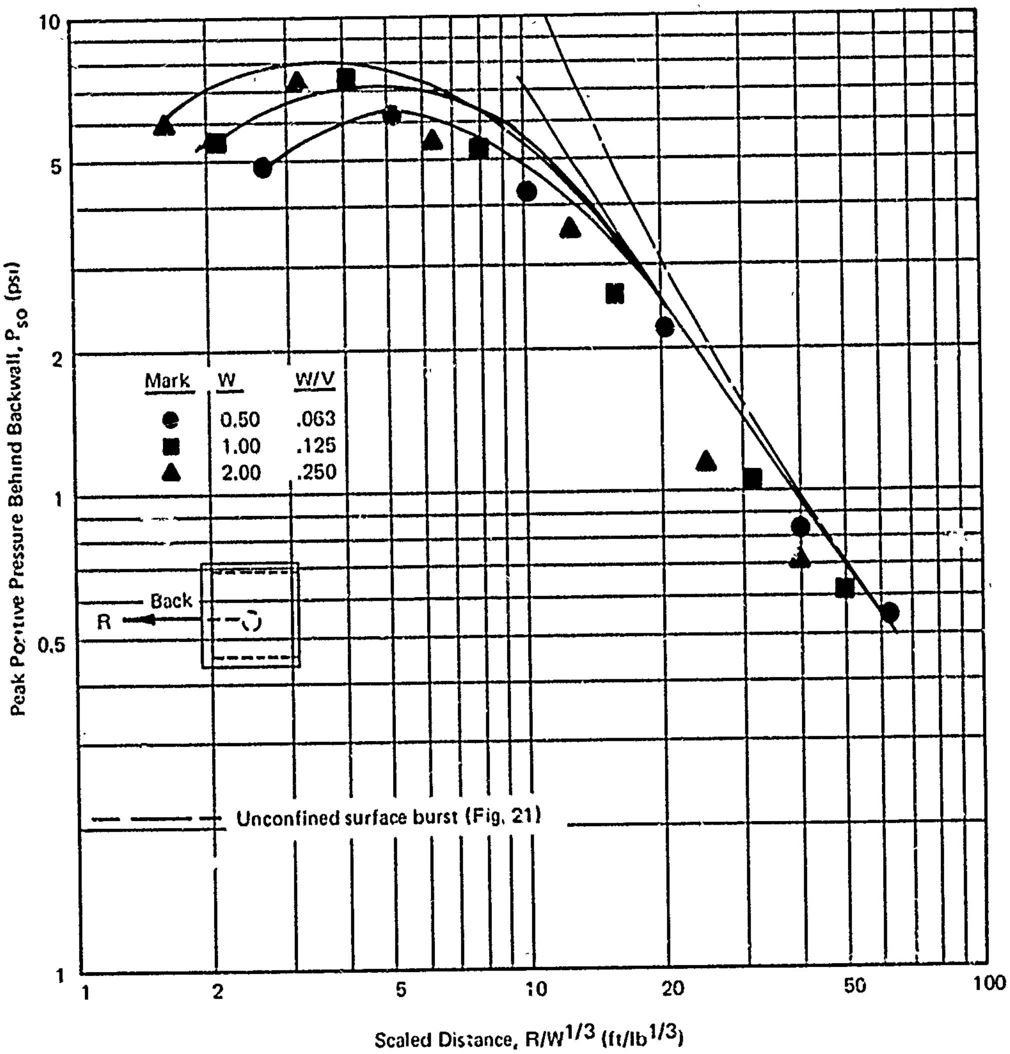


Figure 35. Peak positive pressure behind backwall of small 3-wall cubicle with roof.

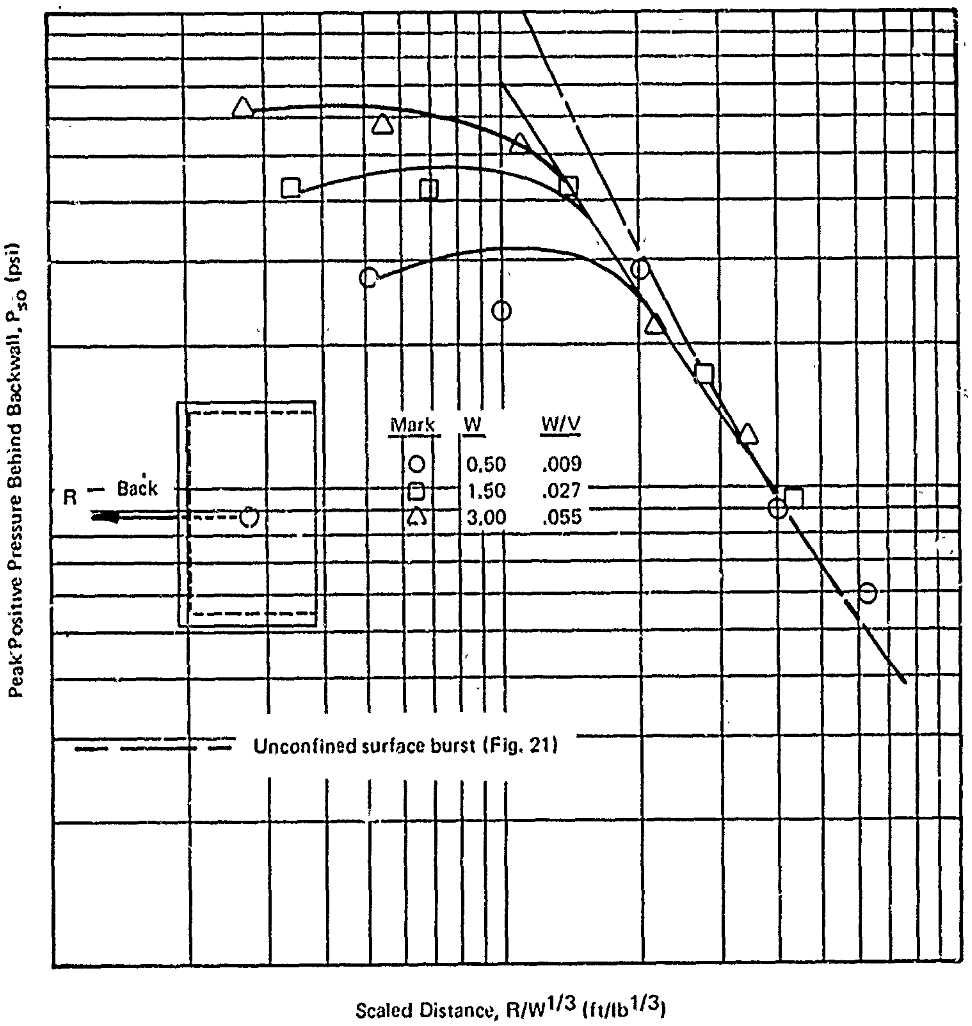


Figure 36. Peak positive pressure behind backwall of large 3-wall cubicle with roof.

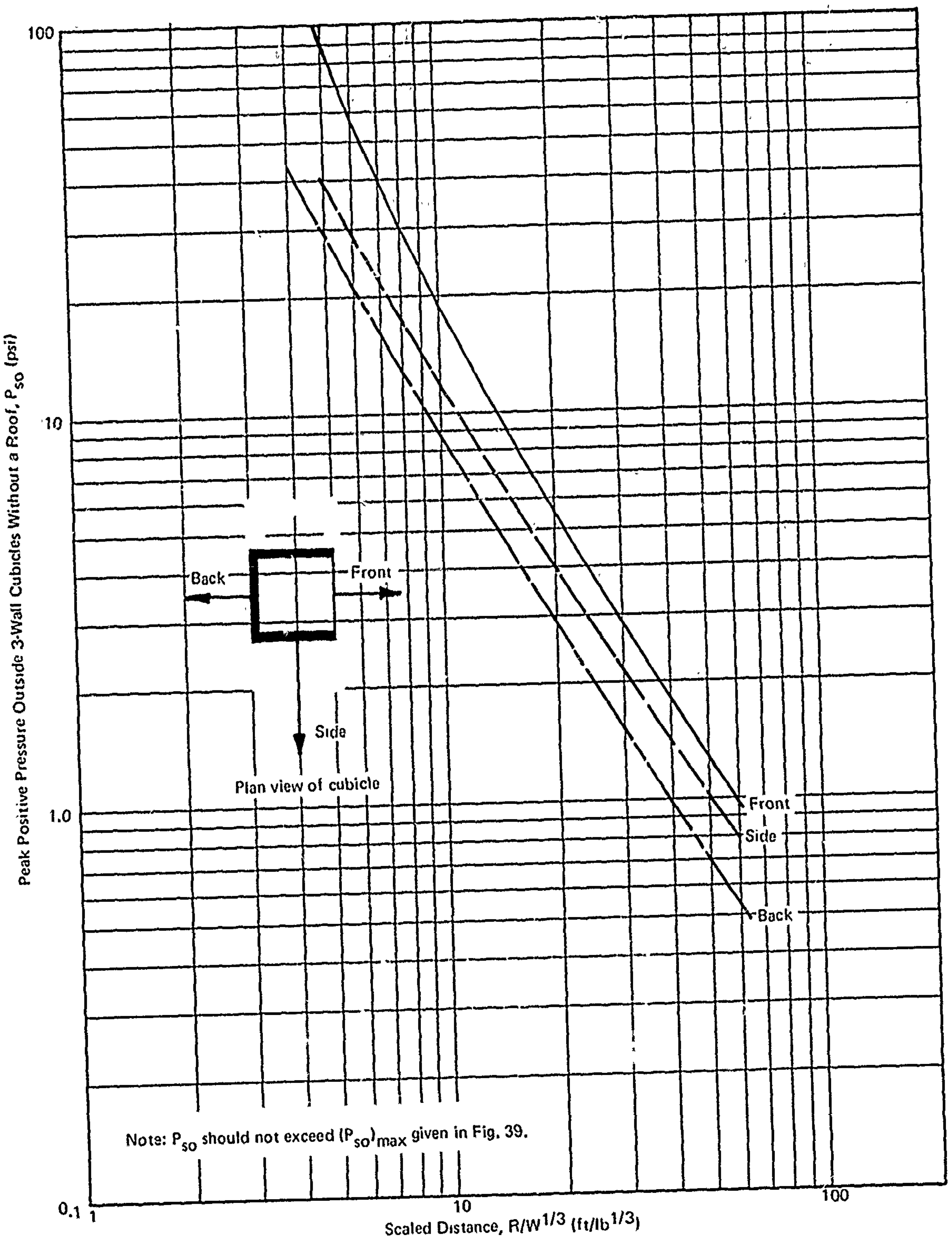


Figure 37. Envelope curves for peak positive pressure outside 3-wall cubicles without a roof.

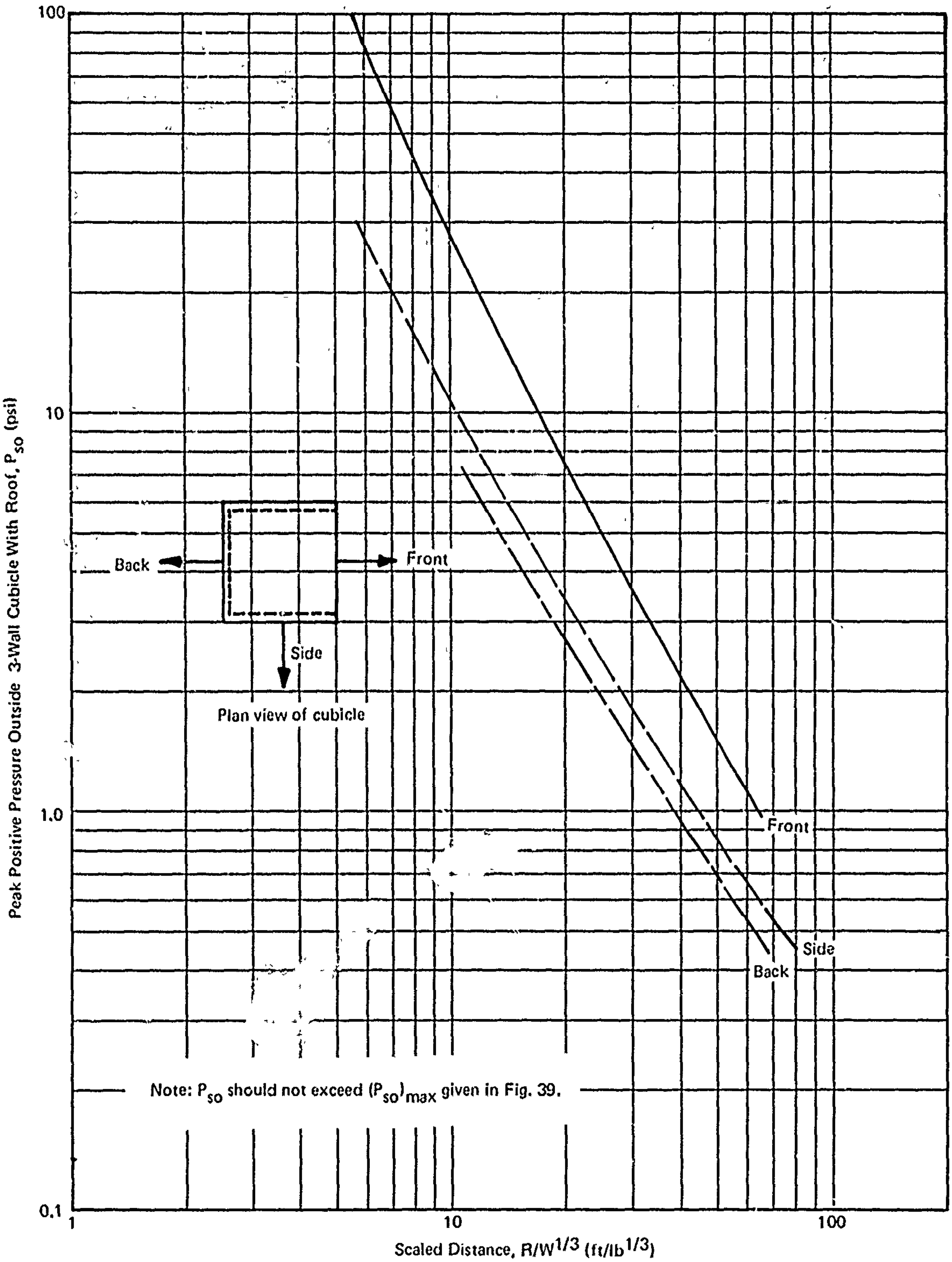


Figure 38. Envelope curves for peak positive pressure outside 3-wall cubicles with a roof.

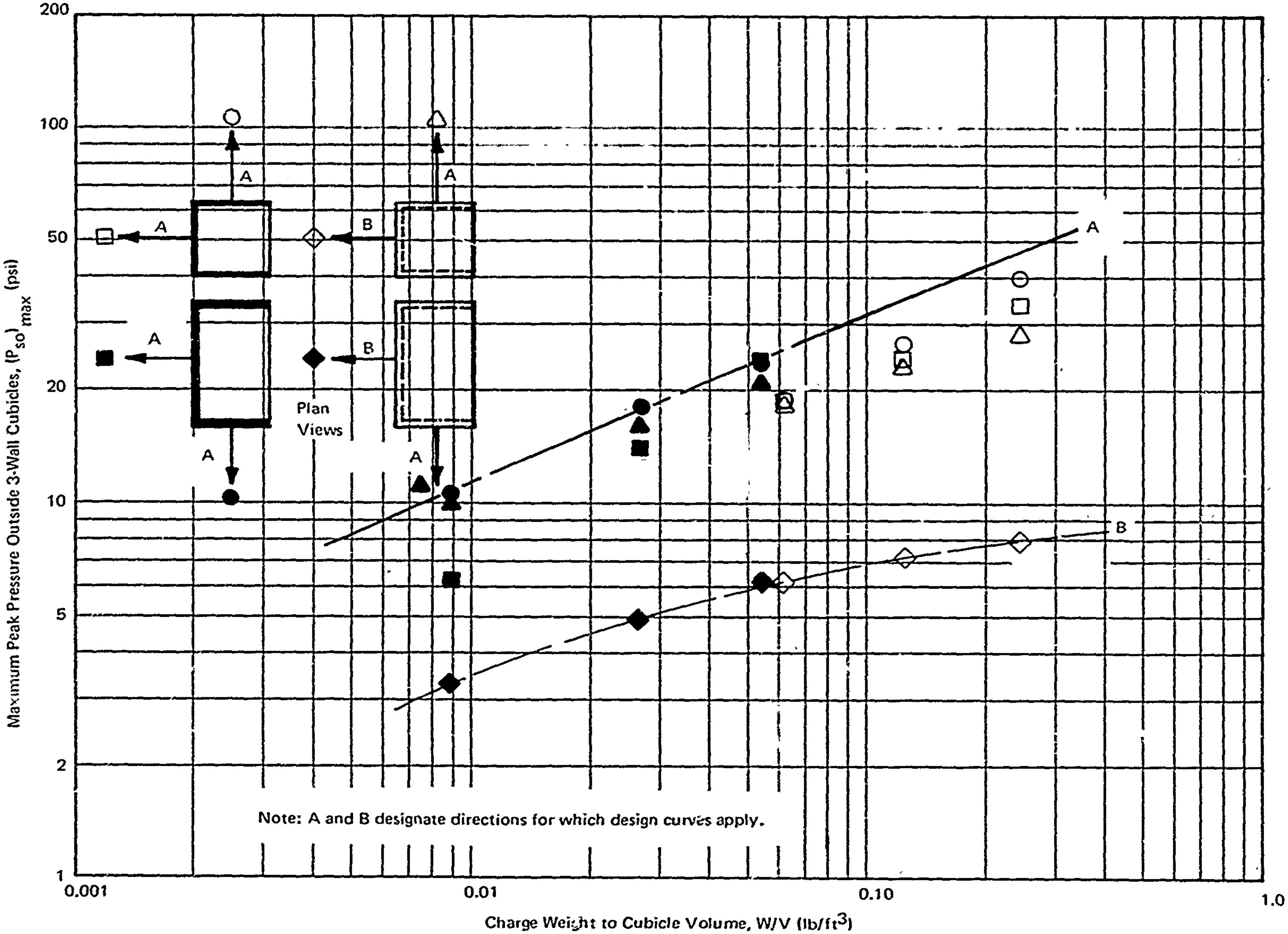
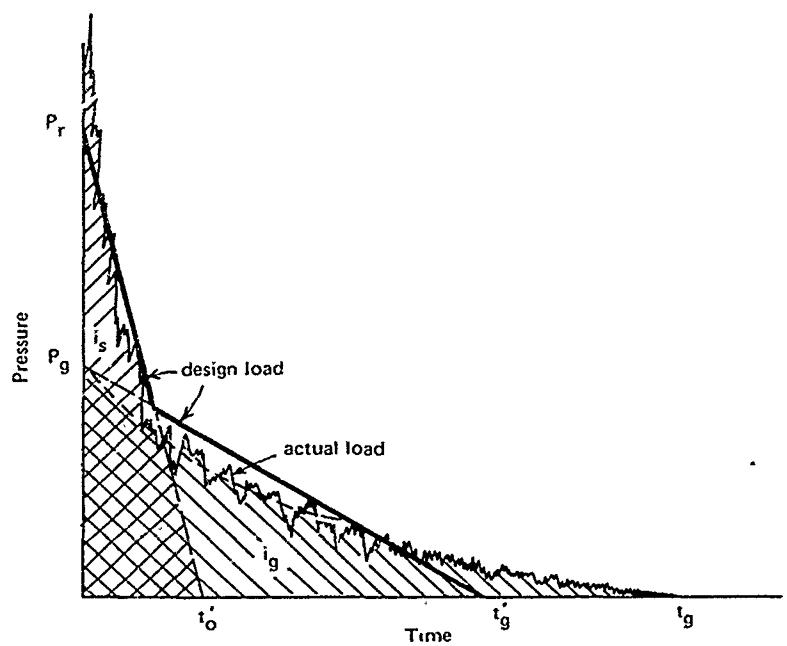
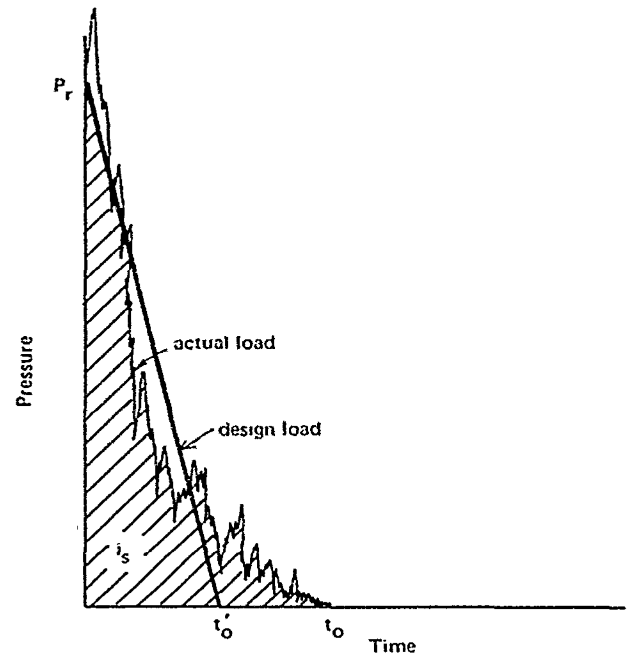


Figure 39. Envelope curves for maximum peak pressure outside 3-wall cubicles.



(a) Inside a partially vented cubicle, $A/V^{2/3} \leq 0.60$.

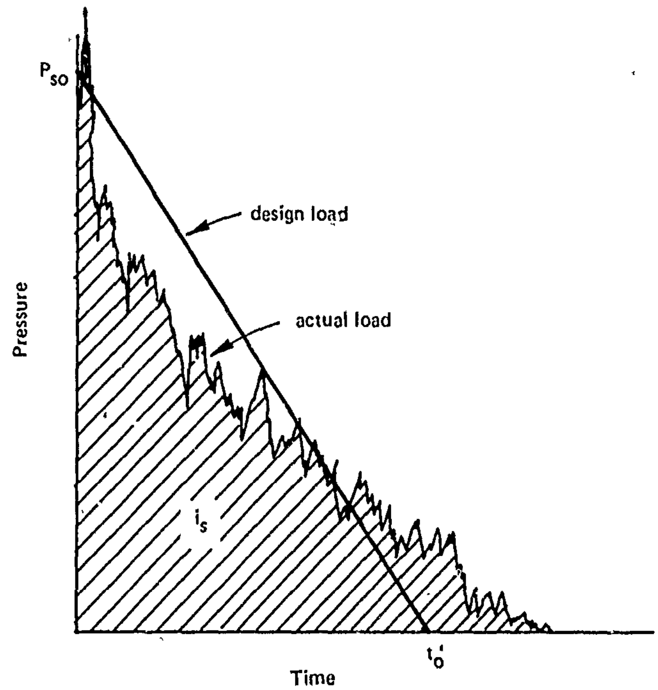


(b) Inside fully vented cubicle, $A/V^{2/3} \geq 0.60$.

Cubicle	i_s	t_o'	P_r	i_g	P_g	t_g'
Fully vented, $A/V^{2/3} \geq 0.60$	Figures 4-17 through 4-62 of TM 5-1300 Design Manual [1]	Equation 4-1 of TM 5-1300 Design Manual [1]	$2i_s/t_o'$	[a]	[a]	[a]
Partially vented, $A/V^{2/3} \leq 0.60$			$2i_s/t_o'$	Figure 14	Figure 10	$2i_g/P_g$

[a] $t_g'/t_o' \leq 1.0$ and, therefore, gas pressure pulse is not a factor in the design loading.

Figure 40. Proposed criteria for design loading inside fully and partially vented cubicles.



Cubicle	Direction	P_{so}	i_s	t_o'
4-wall cubicles with $A/V^{2/3} \leq 1.0$	any	Figure 22[a]	Figure 24[a]	$2i_s/P_{so}$
3-wall cubicles with $A/V^{2/3} \geq 0.60$	behind open front wall	Figures 37, 38 and 39[b]	Equations 8, 9, 11 & 12[b], Figures B-11, 12, 17 & 18[b]	$2i_s/P_{so}$
	behind sidewall		Equations 10 & 13[b] Figures B-13, 14, 19, 20[b]	
	behind backwall		Figures B-15, 16, 21, 22[b]	

[a] For h = 0; for h > 0 see Appendix C.

[b] For h = H; for h < H see Appendix C.

Figure 41. Proposed criteria for design loading outside fully and partially vented cubicles.

CONCLUSIONS

1. Fully and partially vented cubicles can be defined approximately by the dimensionless parameter $A/V^{2/3}$. If $A/V^{2/3} > 0.60$, the cubicle is fully vented ($t_g'/t_o' < 1$), and the gas pressure pulse inside the cubicle is insignificant compared to the shock pressure pulse. If $A/V^{2/3} \leq 0.60$, the cubicle is partially vented ($t_g'/t_o' > 1$), and the gas pressure pulse is an important part of the total loading inside the cubicle.

2. Criteria outlined in Figures 40 and 41 adequately describe the blast loading in and around fully and partially vented cubicles.

RECOMMENDATIONS

The following recommendations for further study are made:

1. Conduct a few well-chosen tests of full-scale cubicles to verify that design charts, equations, criteria, and conclusions drawn from the small-scale model tests apply to large charges in large cubicles. Some test cubicles should be exact prototypes of at least some of the small scale cubicles. Test parameters should include $A/V^{2/3}$, W/V, $R/W^{1/3}$, H, and the location of the charge inside the cubicle. Utilize existing expertise and data recording systems at CEL and computerized data reduction systems and computer programs at the Pacific Missile Range, Point Mugu, California, to minimize the cost of the study.

2. Conduct model tests to determine the influence of h on the blast environment close behind walls of fully and partially vented cubicles. Include 4-wall cubicles with vent pipes of different lengths (h) in the roof and 3-wall cubicles with the ground surface behind the backwall and sidewalls at the elevation of the roof (h = 0) to simulate the roof surface of adjoining buildings.

3. Conduct model tests to determine if large degrees of venting reduce the peak gas pressure inside partially vented cubicles with large values of W/V.

ACKNOWLEDGMENTS

Mr. Richard Rindner of Picatinny Arsenal conceived and administered the study. Mr. Norval Dobbs of Ammann and Whitney provided valuable technical guidance during the program. Testing was conducted at the Pacific Missile Range, Point Mugu, California. The test site was constructed and maintained under the direction of Mr. Vince Gerwe, CEL. Mr. Dale Johnson and Mr. Gerry Duffy of CEL designed, installed, and operated the instrumentation system. Handling and detonation of explosives was supervised by Mr. Paul R. Smith of PMR Operations Department, Launching Division.

Data were digitized and plotted at PMR by the Data Automation Division. Mr. Larry Fuller and Mr. Tom Morris were especially responsible for the outstanding support from PMR in digitizing nearly 2,000 data channels and generating 4,000 data curves in this program.

Appendix A

REPRESENTATIVE PRESSURE- AND IMPULSE-TIME HISTORIES INSIDE AND OUTSIDE THE TEST CUBICLES

PARTIALLY VENTED EXPLOSIONS

Plots in Figures A-1 through A-4 are representative of the blast environment measured inside the 4-wall cubicles and show the effects of increasing the charge weight and vent area. In each plot, the first large spike in the pressure plot is the initial shock pressure produced by the detonation wave. It should be emphasized that the magnitude of this pressure spike is not a true measure of the peak shock pressure since the pressure transducers inside the cubicle were intentionally designed to partially filter and suppress the peak shock pressure reaching the gage. This scheme permitted the use of more sensitive gages to accurately measure the much lower gas pressures. Succeeding spikes and large fluctuations in the pressure plot are shock pressures produced by the reflected shock waves bounding back and forth between the walls, floor, and roof of the cubicle. As the reflected shock waves dissipate their energy, the shock pressure fluctuations dampen out and decay. The fluctuations decay about a mean pressure curve which represents the gas-pressure/time history inside the cubicle. The gas-pressure history is clearly evident after the shock fluctuations have essentially dampened out The characteristic shape of the gas-pressure/time curve is especially clear in the plot representing the largest charge weight and smallest vent area shown in Figure A-1. For a fixed vent area, the plots show the peak gas pressure increased with charge weight and, for a fixed charge weight, the duration of the gas pressure decreased with increasing vent area. When the vent area was increased to a size representing an open-top box (Figure A-4), the shock pressures from multiple shock reflections dominate and there is no clear evidence of any gas pressure, regardless of the charge weight. If indeed gas pressures do exist in the open-top box, they are completely clouded in the plot by the multiple shock-pressure fluctuations.

The impulse-time trace is a smooth curve in every plot describing the blast environment inside the 4-wall cubicles. The impulse curve gradually rises and reaches a peak value at a time corresponding to the duration of the positive pressure, except when the gage was affected by temperature. In this case, the impulse curve continually increases with time, as illustrated by the plots in Figures A-1 and A-2 for $W = 2.0$ pounds. In plots which clearly show gas pressures, such as those in Figures A-1 and A-2, the total impulse of the first shock-pressure spike is almost insignificant compared to the maximum positive impulse; for small degrees of venting, most of the maximum impulse is contributed by the gas pressure. Of course, as the vent area increases, the gas impulse decreases until at very large vent areas, such as $A/V = 0.50$ (open-top box) the gas pressure impulse is insignificant; for large degrees of venting, most, if not all, of the maximum impulse is contributed by the shock pressures.

Plots in Figures A-5 through A-10 are representative of the blast environment measured outside the 4-wall cubicles and show the effects of increasing the vent area and distance from the charge. In the area close to the cubicle, the pressure-time history consists of an initial large pressure spike of very short duration followed by high-frequency pressure fluctuations of decreasing magnitude (see Figures A-5 and A-6). This train of pressure spikes is apparently caused by the detonation wave, followed by reflected shock waves, escaping through the vent hole in the cubicle. Notice that with increasing distance from the charge, the train of shock waves apparently merge because the number of pressure spikes decreases, until at large distances (Figures A-9 and A-10) there are only a few dominant pressure spikes. At this far distance, the duration of the first and succeeding spikes is much longer; the peak positive pressure and impulse are much lower; and the duration of the positive pressure is very pronounced. Regardless of the vent area or charge weight, the peak negative pressure is relatively low and decreases with distance. Although the duration of the negative pressure phase is not well-defined, the duration appears to increase slightly with distance from the charge.

FULLY VENTED EXPLOSIONS

Three-Wall Cubicles Without Roof (S3W and L3W)

Plots in Figures A-11 through A-22 are representative of the blast environment measured outside the small and large 3-wall cubicles without a roof. Figures A-11 through A-16 apply to the small 3-wall cubicle; Figures A-17 through A-22 apply to the large 3-wall cubicle. The plots are arranged for ease in comparing the blast environment at a fixed distance out the front, and behind the sidewalls and the backwall.

Close to the cubicle, as in Figures A-11, A-12, A-17 and A-18, the peak positive pressure and impulse are greatest out the open front, substantially less behind the sidewalls, and least behind the backwall. Note carefully in the figures that peak pressures just beyond the open front are greatest by a factor of 15 or more, but the maximum impulses are greatest by a factor of only about 3 or 4. This fact is important for design because the response of most structures to such short durations would depend on the total impulse, not the peak pressure. The reverse is generally true for personnel. Since ear drums have a relatively high-frequency response capability, ear drum damage is more apt to depend on the peak pressure.

At large distances (Figures A-15, A-16, A-21, and A-22), the peak pressure and impulse are much less: out the front and behind the sidewalls the pressure-time histories have the characteristic shape of an unconfined explosion with the peak pressure, decay rate, and positive-phase duration very distinct. However, the pressure-time history behind the backwall is not so characteristic since it still exhibits two distinct pressure spikes.

Peak negative pressures are about the same in all directions and decrease with distance from the charge. The duration of the negative phase is greatest out the front, slightly less behind the sidewall, and least behind the backwall.

Close to both cubicles, the pressure-time history behind the sidewall contains 3 distinct spikes. The peak pressure of the second spike is greater than the first, as shown in Figures A-11, A-12, A-17, and A-18. At a scaled distance somewhere between 8.0 and 16.0 ft/lb$^{1/3}$, as in Figures A-13, A-14, A-19, and A-20, these shock waves have merged and the pressure history exhibits the characteristic shape of an unconfined explosion. Pressure fluctuations are greatest behind the backwall, but the number of pressure spikes decreases with distance until at a distance of 50 ft/lb$^{1/3}$ there are only two spikes, as in Figures A-15, A-16, A-21, and A-22.

The impulse-time curves for all directions are smooth curves. The maximum positive impulse, in most cases, occurs when the pressures first become negative. Succeeding pressure spikes occasionally delayed the peaking of the impluse curve and therefore also increased the positive phase duration (by definition). Behind the backwall, the impulse curves for any distance appear to rise and fall at about the same rate, while out the open front, the impulse curves decay two to four times more slowly than they rise.

There are no major differences between the small and large cubicles; the shapes of the pressure- and impulse-time curves in corresponding directions are essentially the same.

Three-Wall Cubicles With Roof (S3WR and L3WR)

Plots in Figures A-23 through A-34 are representative of the blast environment measured outside the small and large 3-wall cubicles with a roof. Figures A-23 through A-28 apply to the small 3-wall cubicle; Figures A-29 through A-34 apply to the large 3-wall cubicle. The plots are arranged for ease in comparing the blast environment at a fixed distance out the front, and behind the sidewalls and the rear wall.

Close to the cubicles (Figure A-23 and A-24), the peak positive pressure and impulse are greatest out the open front, substantially less behind the sidewalls, and least behind the backwall. Also, the positive phase duration is very short out the front compared to the sidewalls and rear wall. The magnitude and duration of negative pressures are the same order of magnitude behind both the backwall and sidewalls.

With increasing distance from the charge, pressures drop and durations increase in all directions from the cubicle. Note in each figure that the peak positive pressures and impulses out the front, and behind the sidewall and the backwalls maintain their

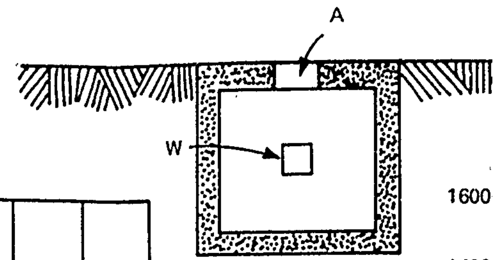
same relative strength with increasing distance from the charge. Even at large distances (Figures A-27, A-28, A-33 and A-34) the positive pressure and impulse are still greatest out the front of the cubicle.

A comparison of Figures A-11 and A-12 with Figures A-23 and A-24 shows the effect of adding a roof to a 3-wall cubicle. By adding the roof, the peak positive pressure and impulse increased out the front, were essentially the same behind the sidewalls, and dramatically decreased behind the backwalls. The effect of the roof was most dramatic at points close to the cubicle.

A comparison of Figures A-23 and A-24 with A-29 and A-30 shows some of the effect of cubicle geometry. Close to the large rectangular-shaped cubicle (Figures A-29 and A-30), three distinct pressure spikes exist, especially out the open front. These spikes are not as pronounced close behind the walls of the small cube-shaped cubicle (Figures A-23 and A-24). With increasing distance, the rear spikes, traveling through more dense air, have a higher velocity, and therefore overtake and merge with the front shock wave as illustrated by the smooth shape of the pressure and impulse curves shown in Figures A-33 and A-34.

Blast Environment Inside 3-Wall Cubicle (L3W)

In a few tests, pressure was measured at one point inside the large 3-wall cubicle without a roof. The pressure transducer was located in one wing wall at a point located $5L_s/6$ from the backwall and H/2 from the floor. Plots in Figures A-35 and A-36 are representative of the measured pressure and computed impulse-time histories. Notice that the plots do not show clear evidence of gas pressures, and the pressure traces have about two or three low-frequency spikes in the positive phase. Apparently these three spikes represent the shock reflections off the backwall, the opposite wing-wall and the floor, all arriving at the gage at slightly different times because of the difference in the distance and orientation of each reflecting surface relative to the transducer. In all cases, the positive phase is reasonably well-defined; and it corresponds to the time of peak positive impulse. It was shown in the report that these few measurements were invaluable in establishing relationships which describe the blast environment inside cubicles. The measured peak positive pressure shown in Figures A-35 and A-36 are no doubt much lower than the actual peak pressure since the transducer was equipped with a filter; however, the durations and time variations of the actual pressure are accurate.



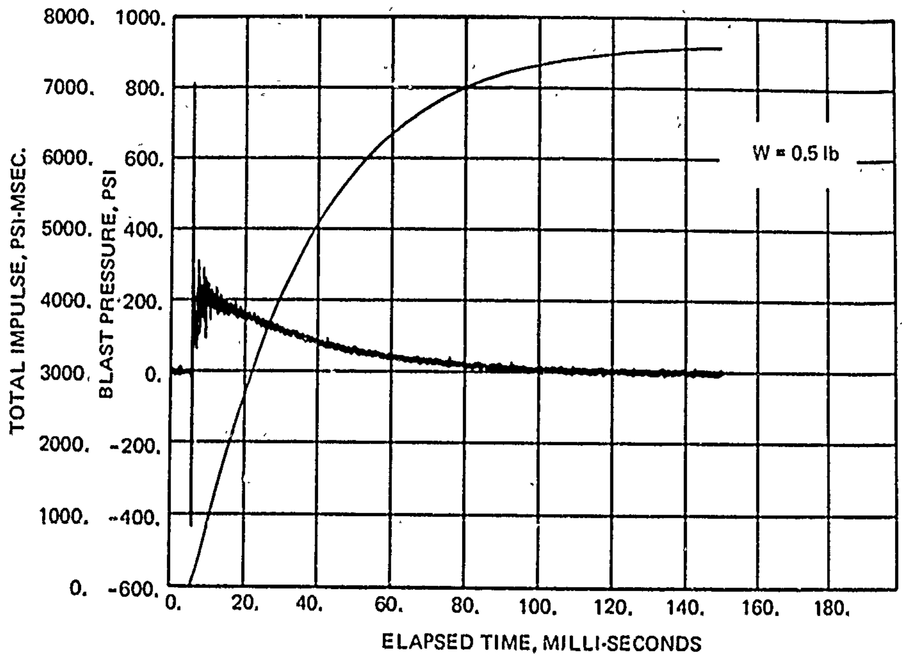


Figure A-1. Blast er

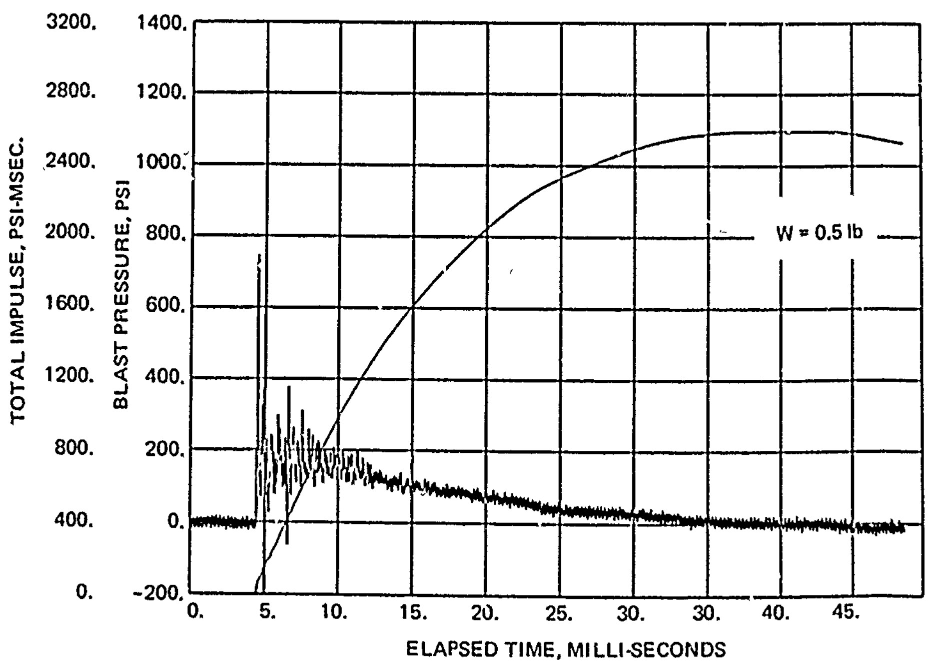
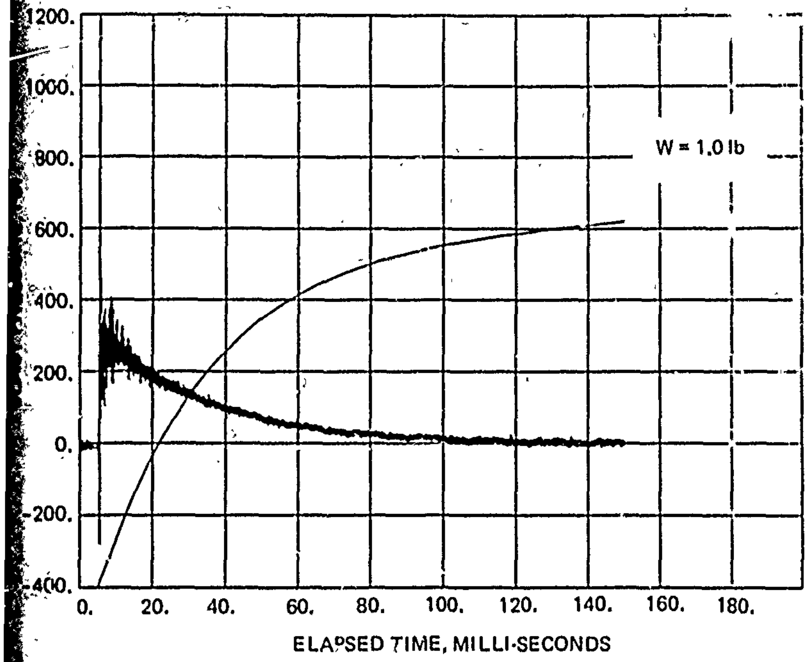
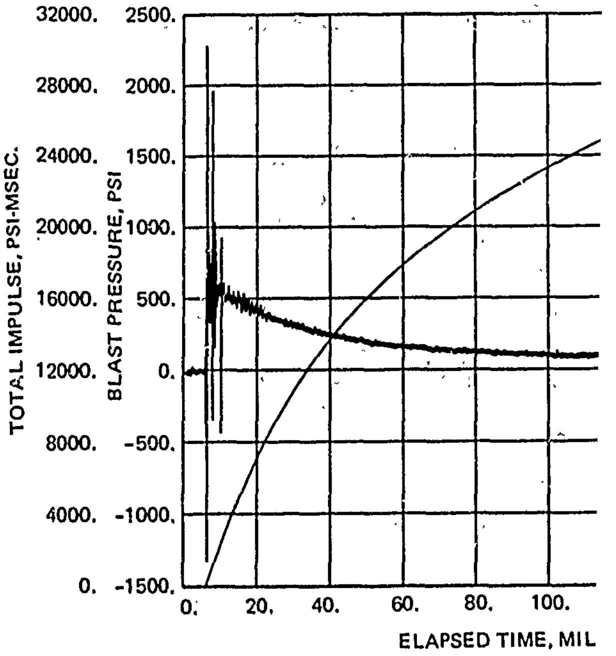
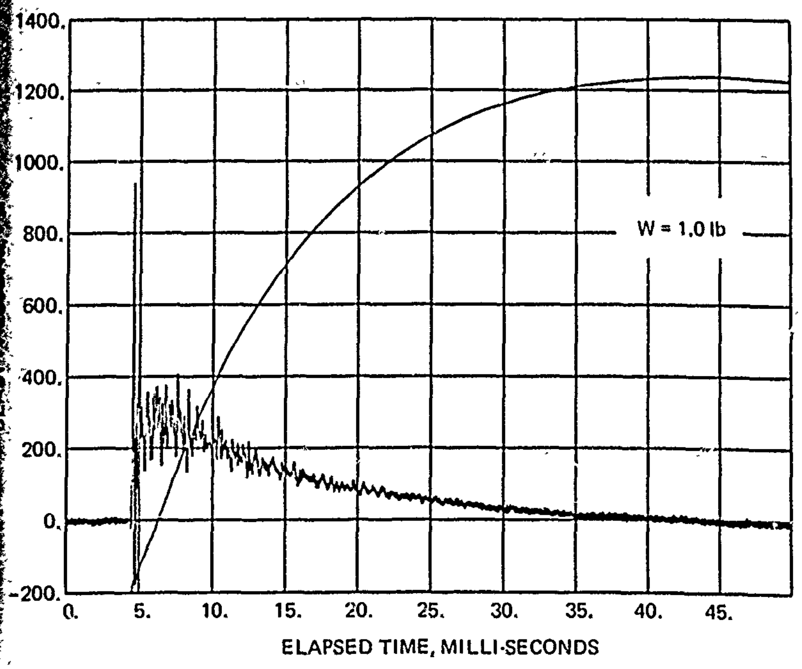


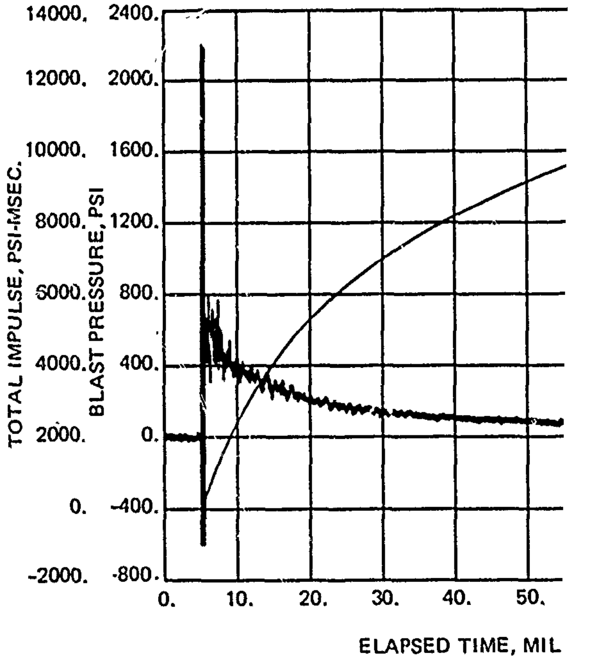
Figure A-2. Blast e



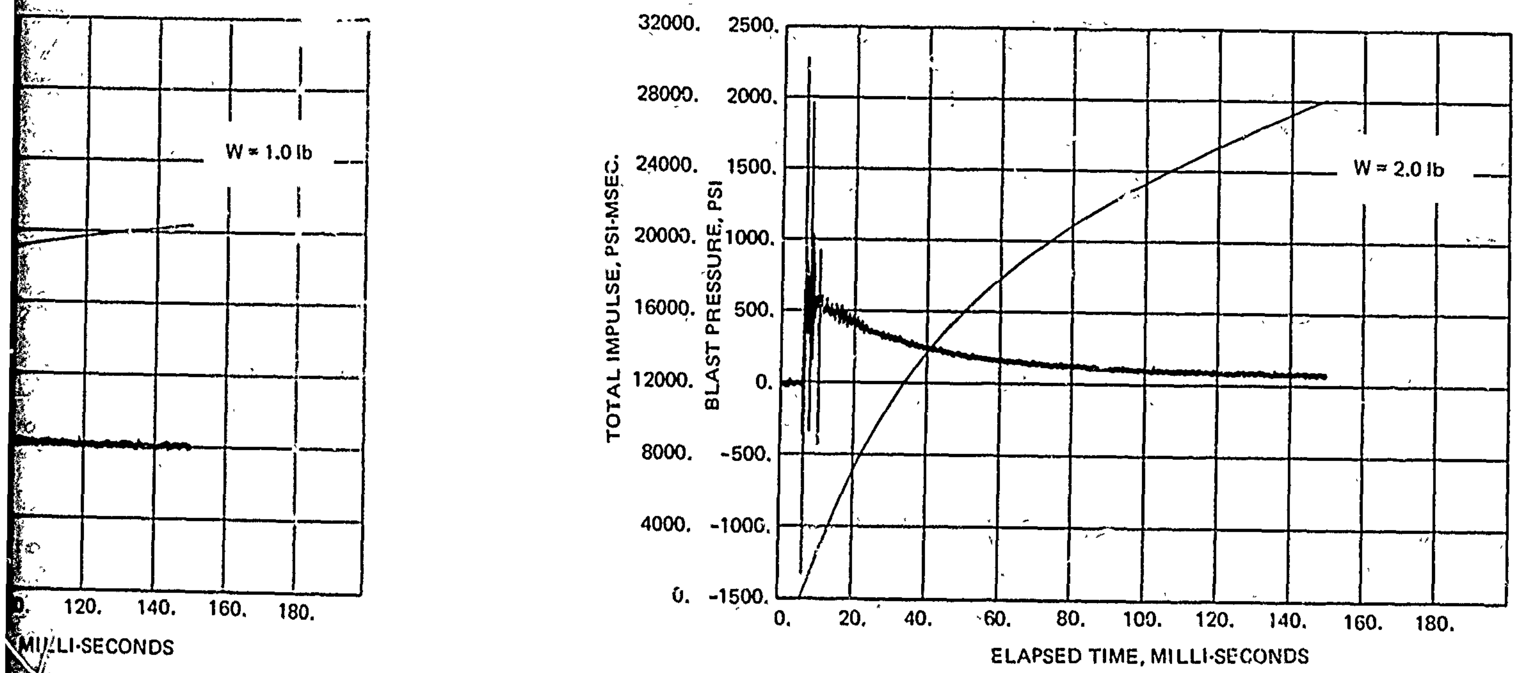


nment inside 4-wall cubicles: explosive charges of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.02$.

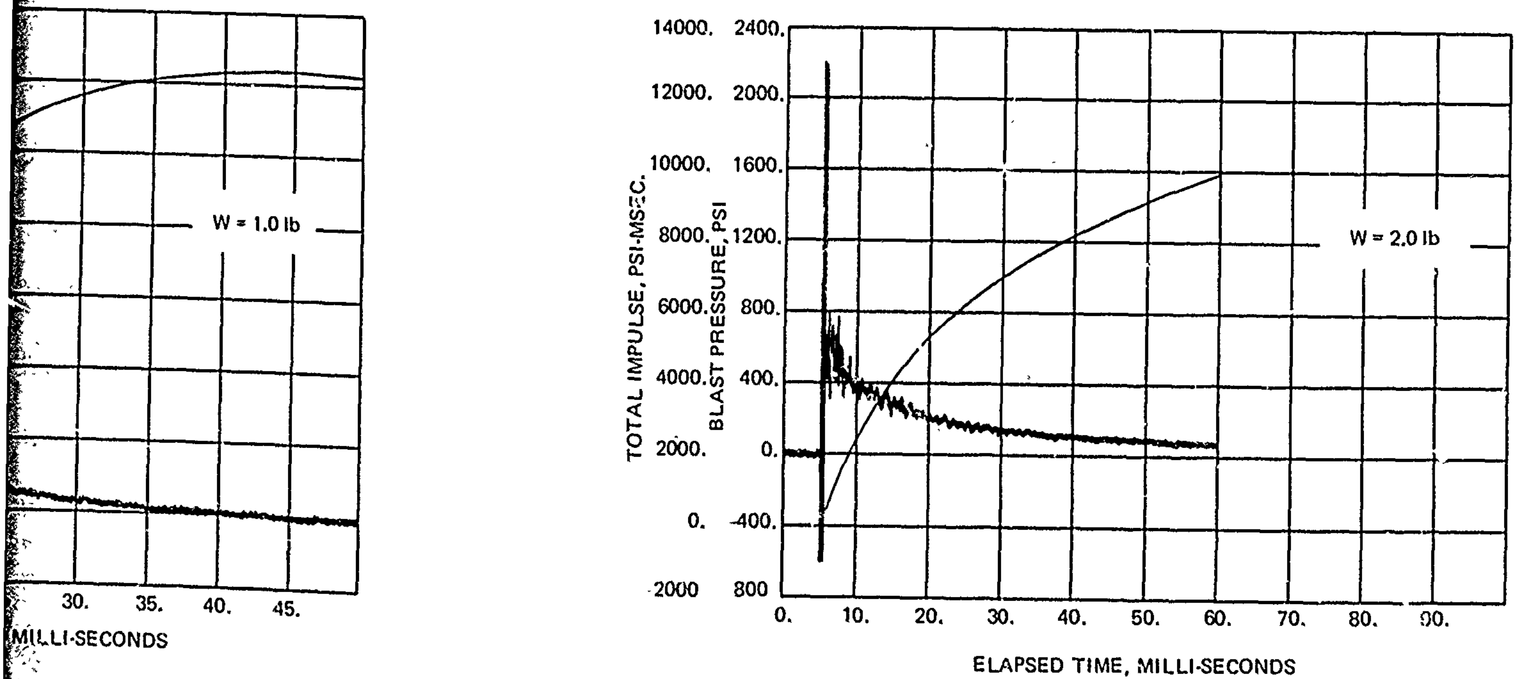




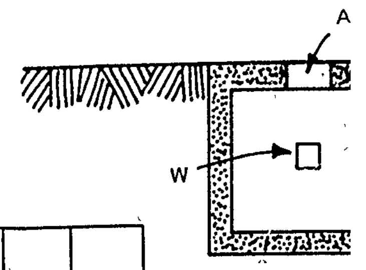
ironment inside 4-wall cubicles: explosive charges of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.06$.

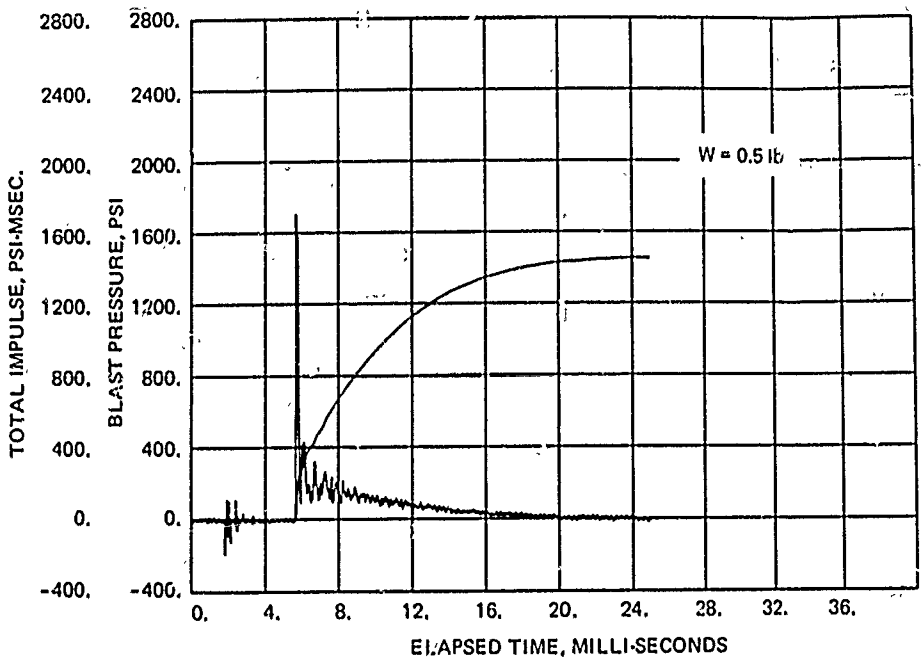


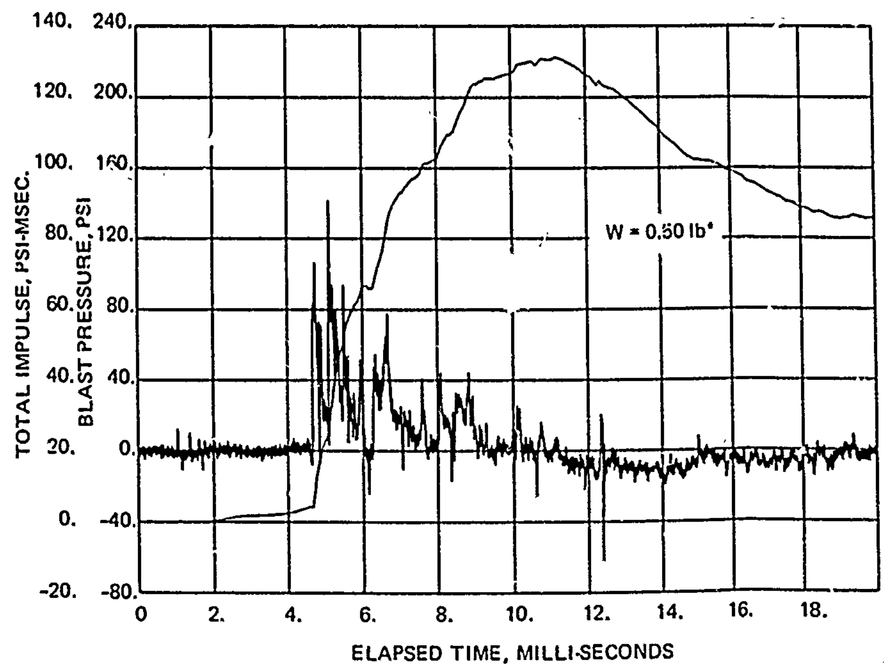
...es of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.02$.



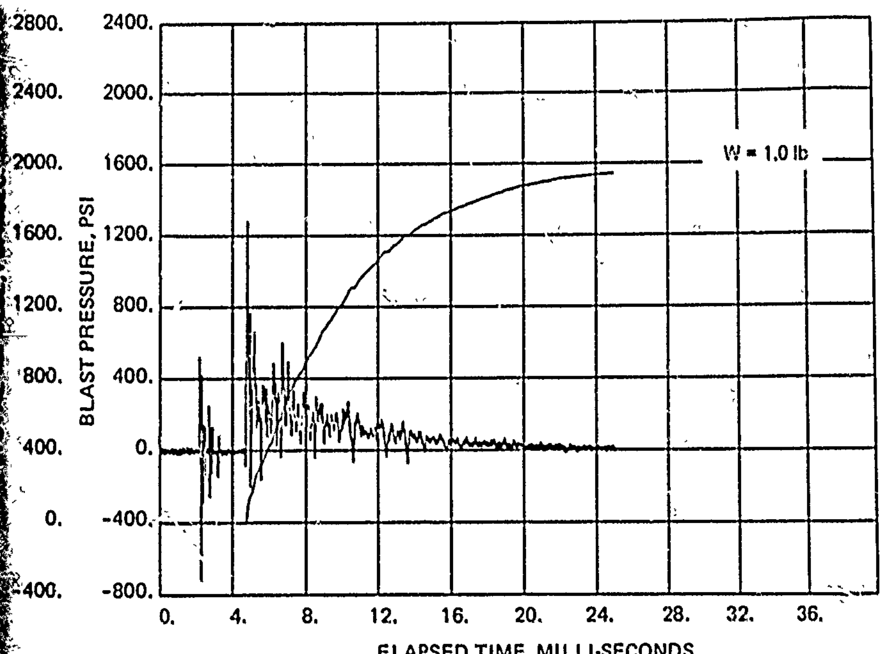
...arges of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.06$.

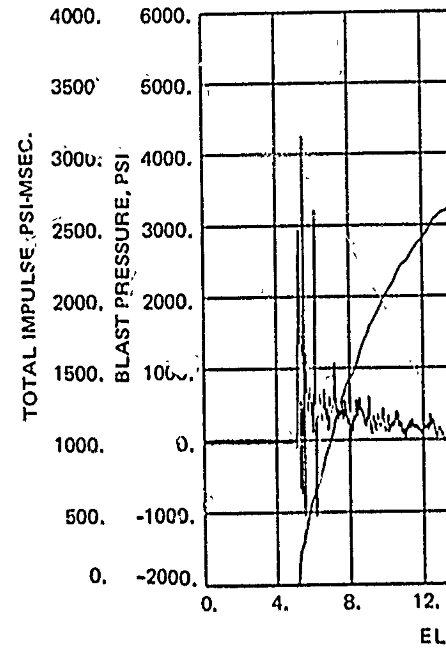

A
W


TOTAL IMPULSE, PSI-MSEC.
BLAST PRESSURE, PSI
2800.
2400.
2000.
1600.
1200.
800.
400.
0.
-400.
W = 0.5 lb
0.
4.
8.
12.
16.
20.
24.
28.
32.
36.
ELAPSED TIME, MILLI-SECONDS

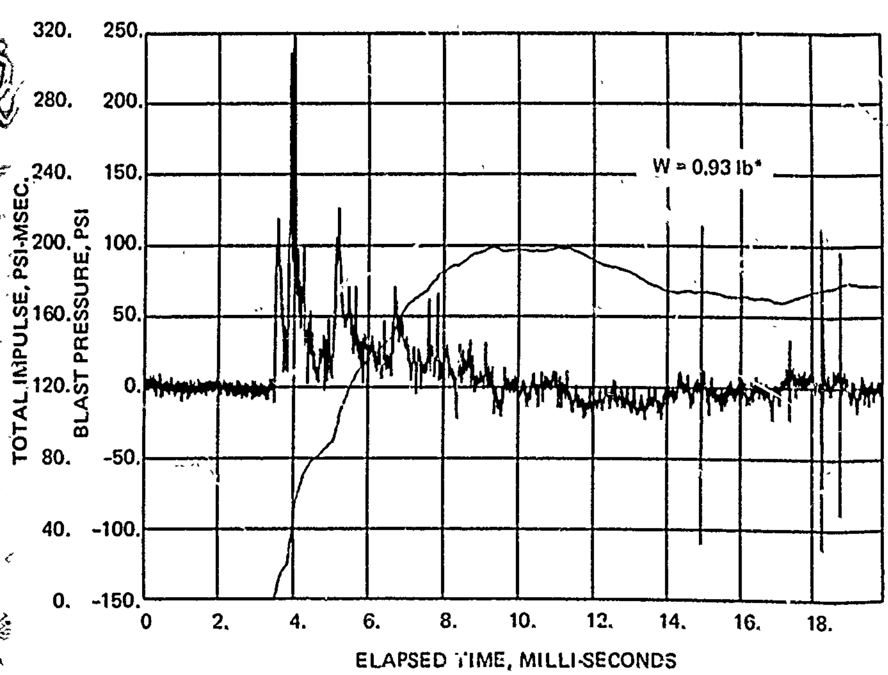

TOTAL IMPULSE, PSI-MSEC.
BLAST PRESSURE, PSI
140.
120.
100.
80.
60.
40.
20.
0.
-20.
240.
200.
160.
120.
80.
40.
0.
-40.
-80.
W = 0.50 lb*
0
2.
4.
6.
8.
10.
12.
14.
16.
18.
ELAPSED TIME, MILLI-SECONDS

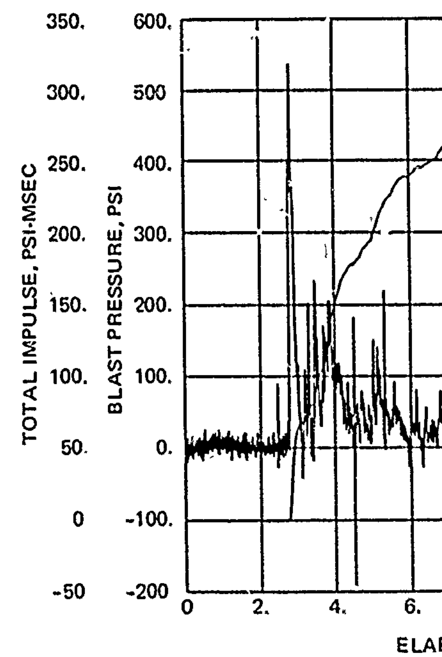
Fi



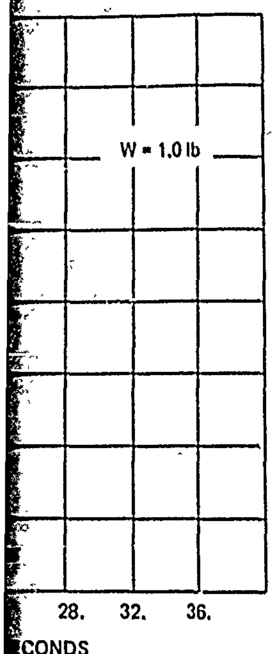


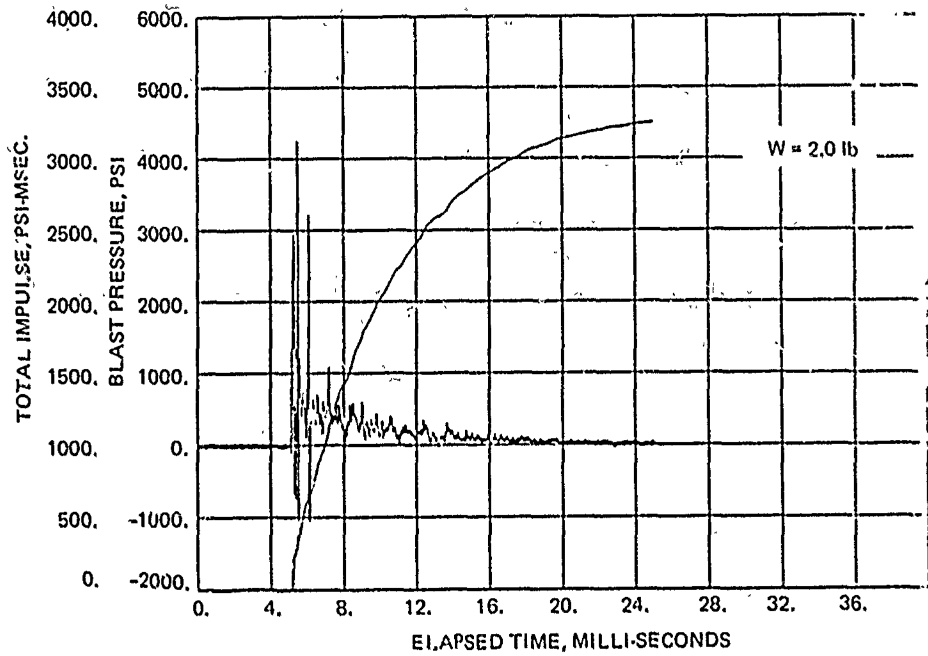
-3. Blast environment inside 4-wall cubicles: explosive charges of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.18$.



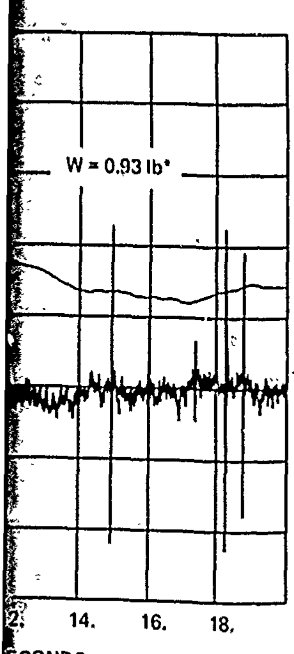


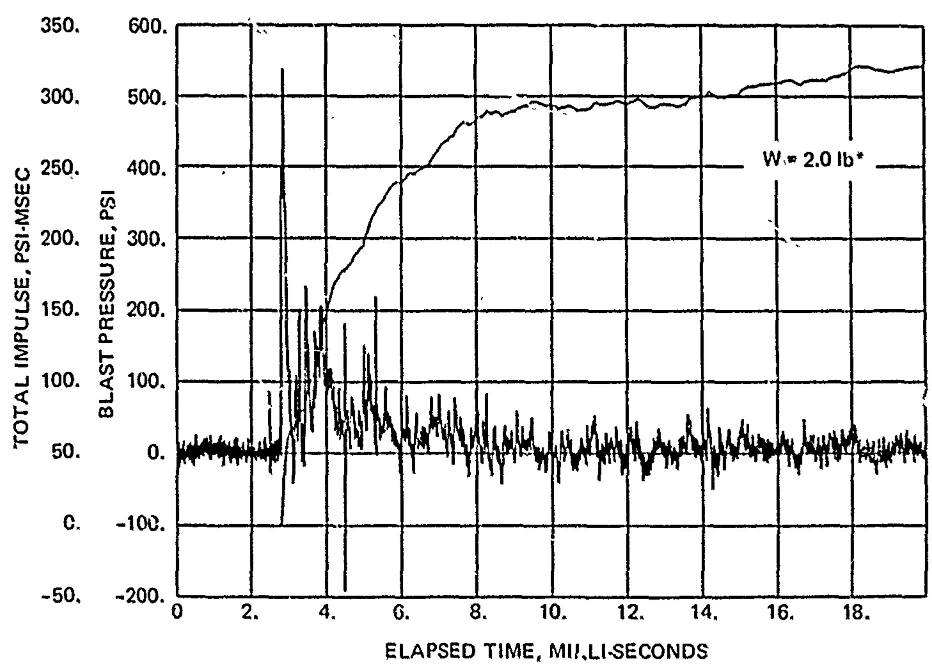
Blast environment inside 4-wall cubicles: explosive charges of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.77$.
Note: Data are from tests described in Ref 6 f r open-top box with $V = 116\ ft^3$.



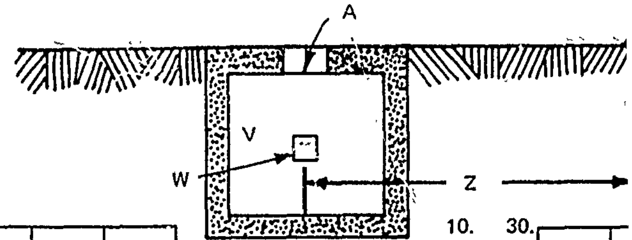


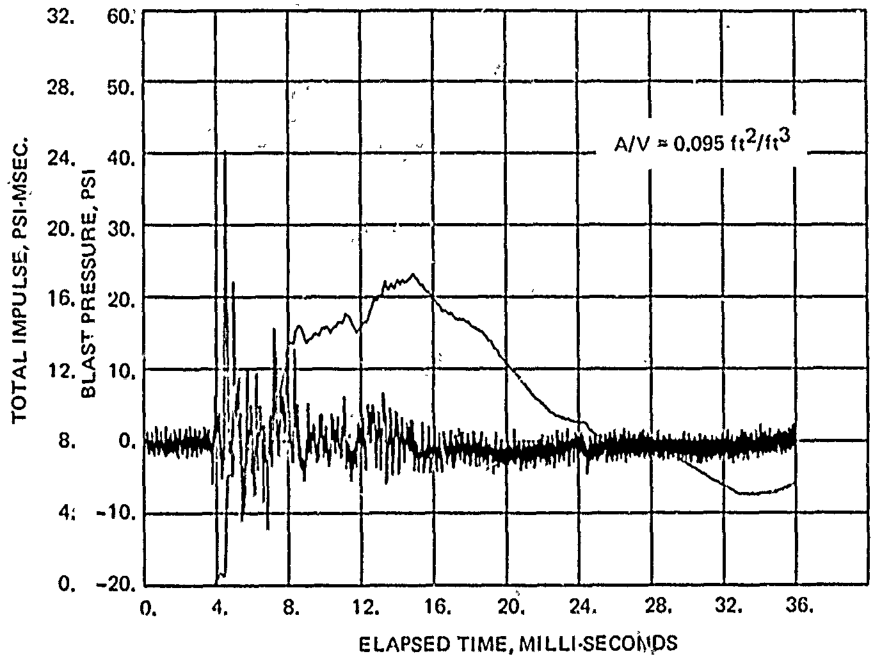
es of 0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.18$.





0.5, 1.0, and 2.0 pounds; $A/V^{2/3} = 0.77$.
with $V = 116$ ft^3.





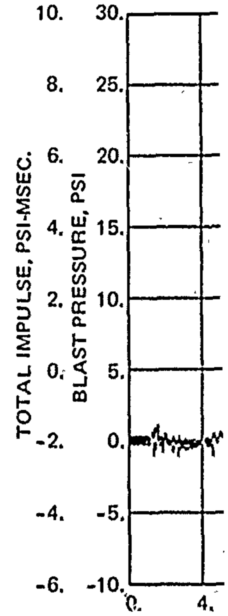
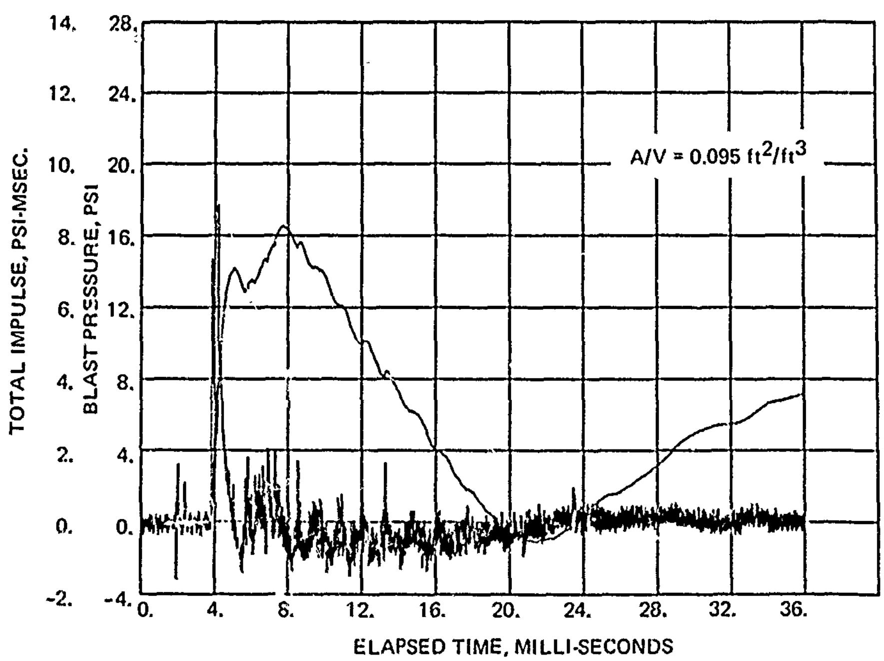


Figure A-5. Blast environment outside 4-w



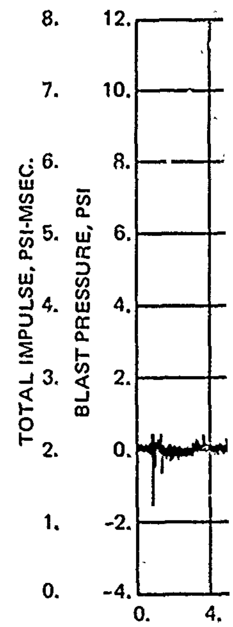
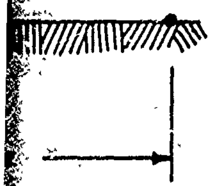
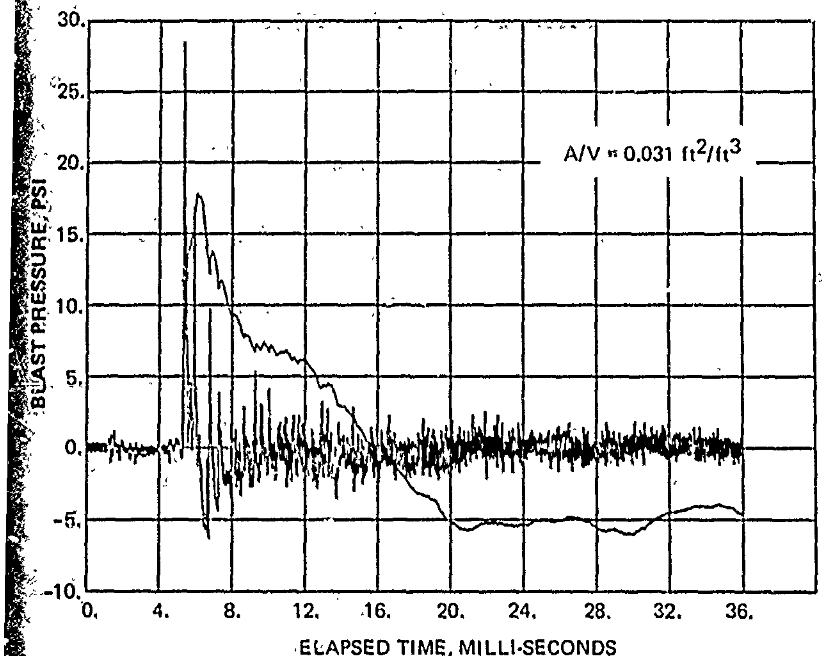
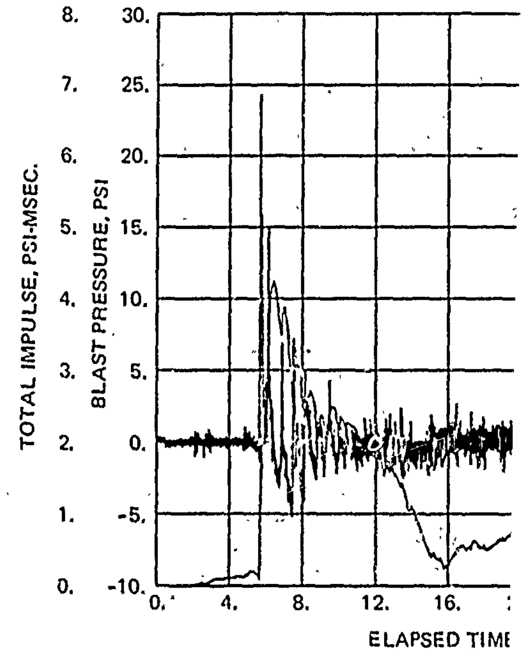


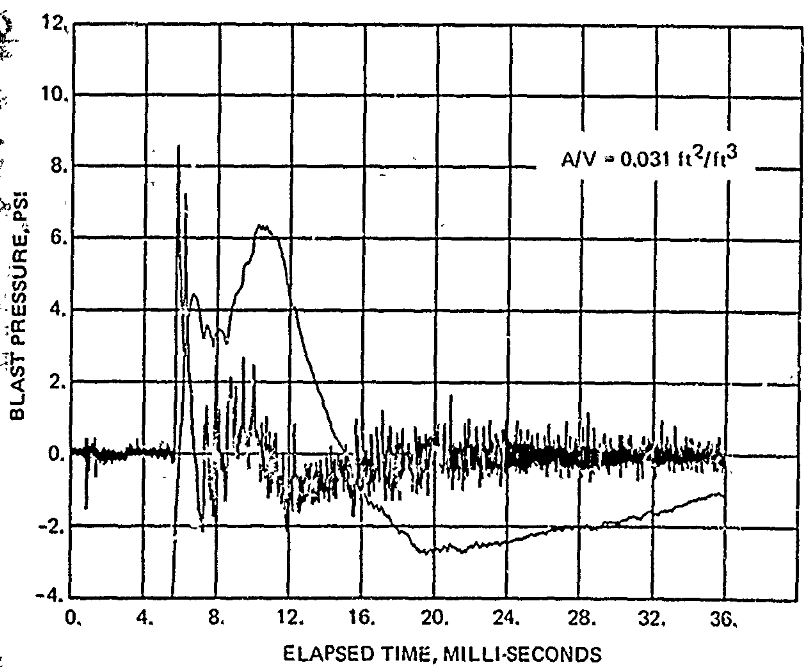
Figure A-6. Blast environment outside 4-wal

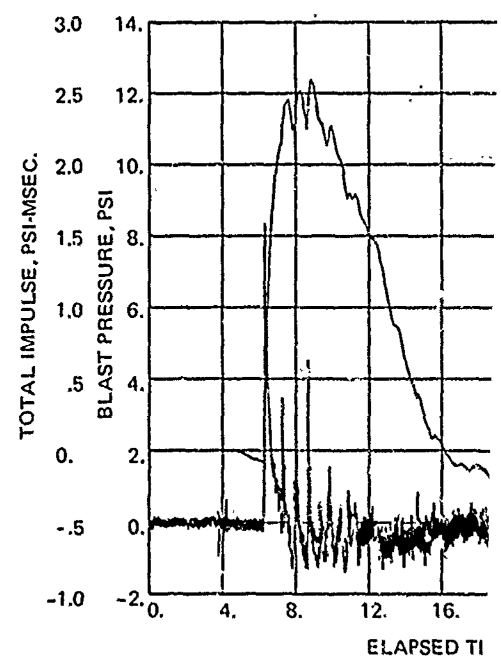




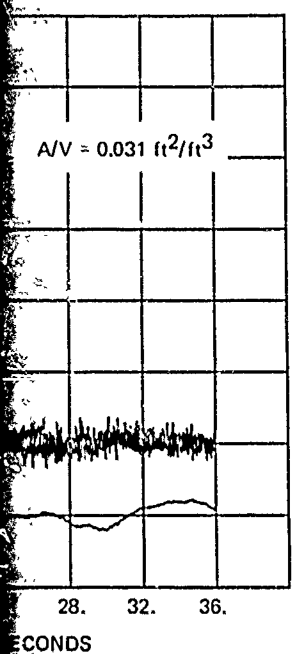


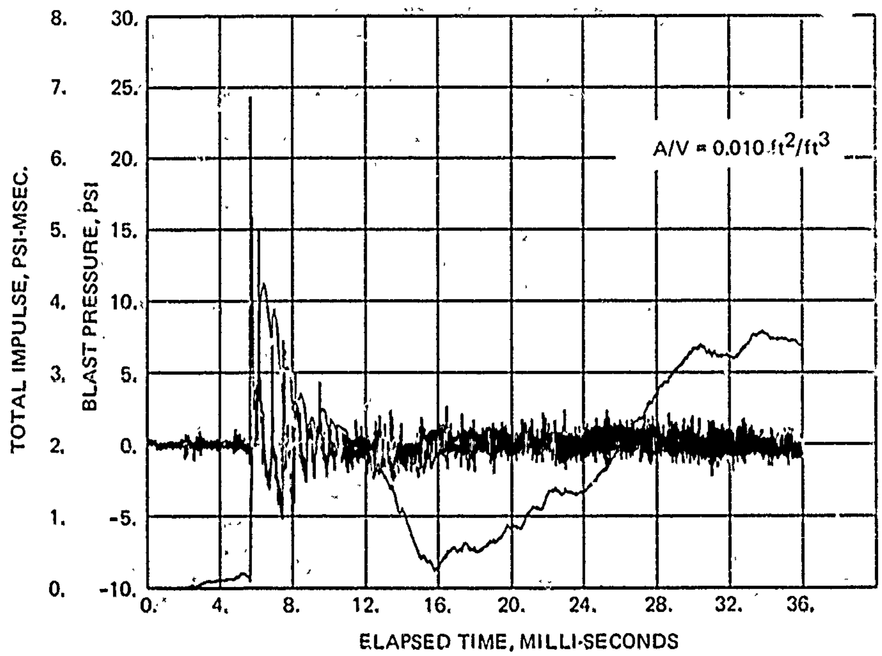
ent outside 4-wall cubicles: explosive charges of 1.0 pound; various degrees of venting; Z = 2.00 ft/lb$^{1/3}$.



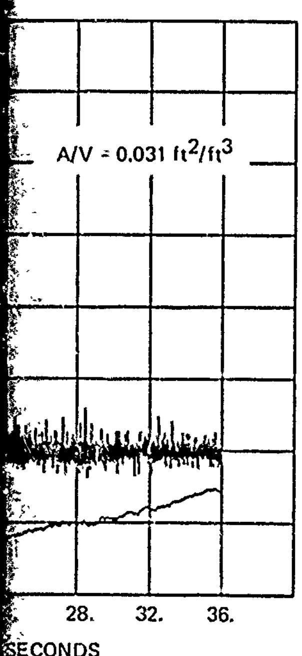


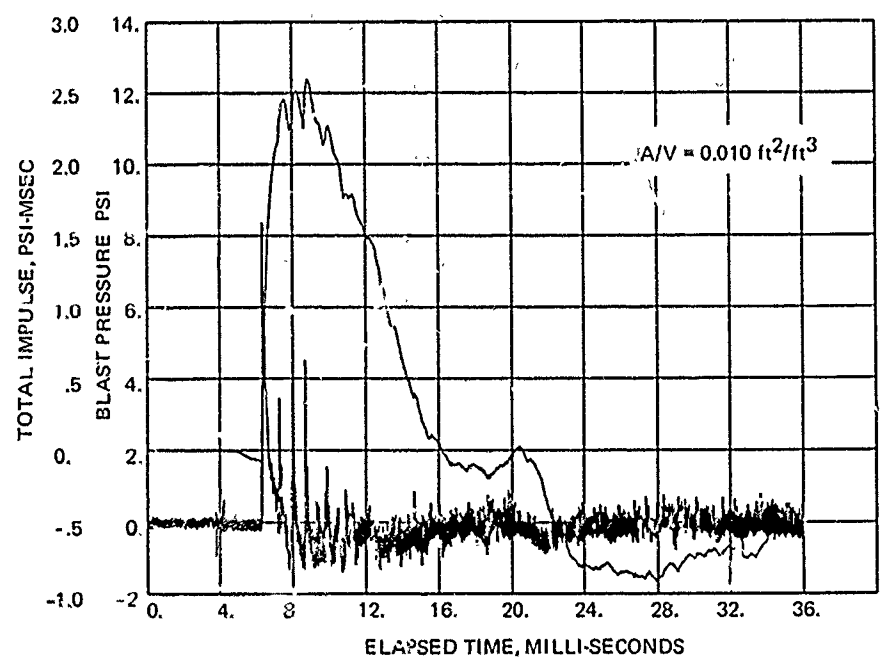
ment outside 4-wall cubicles: explosive charges of 1.0 pound; various degrees of venting, Z = 4.00 ft/lb$^{1/3}$.



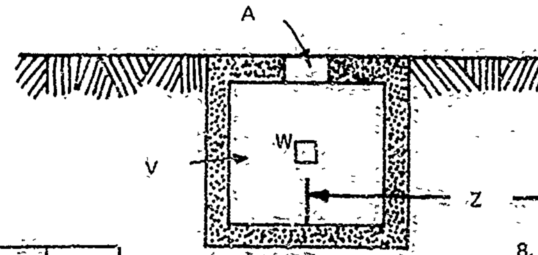


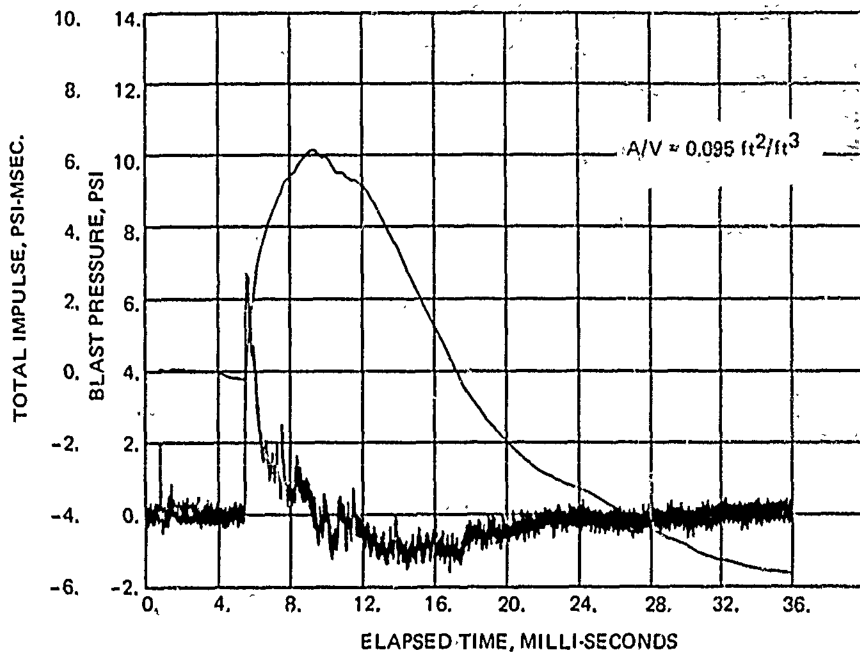
0 pound; various degrees of venting; $Z = 2.00\ \mathrm{ft/lb^{1/3}}$.





pound; various degrees of venting; $Z = 4.00\ \mathrm{ft/lb^{1/3}}$.





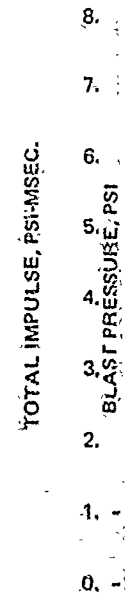
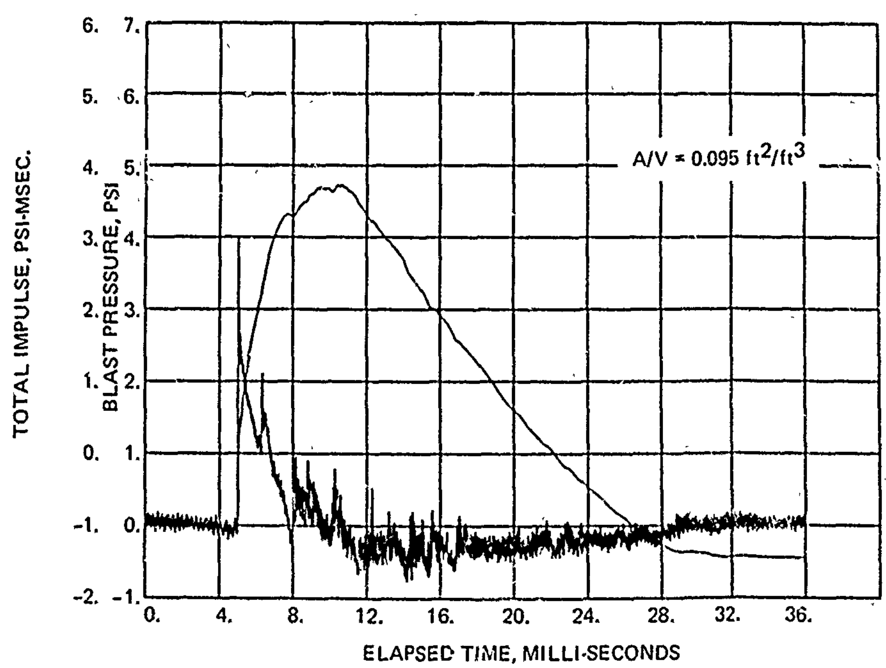


Figure A-7. Blast environm



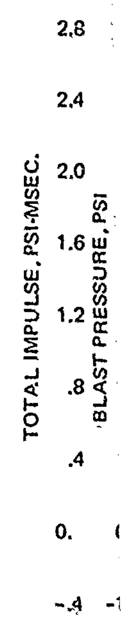
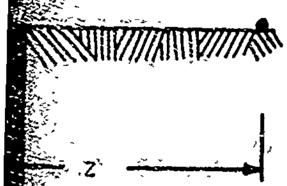
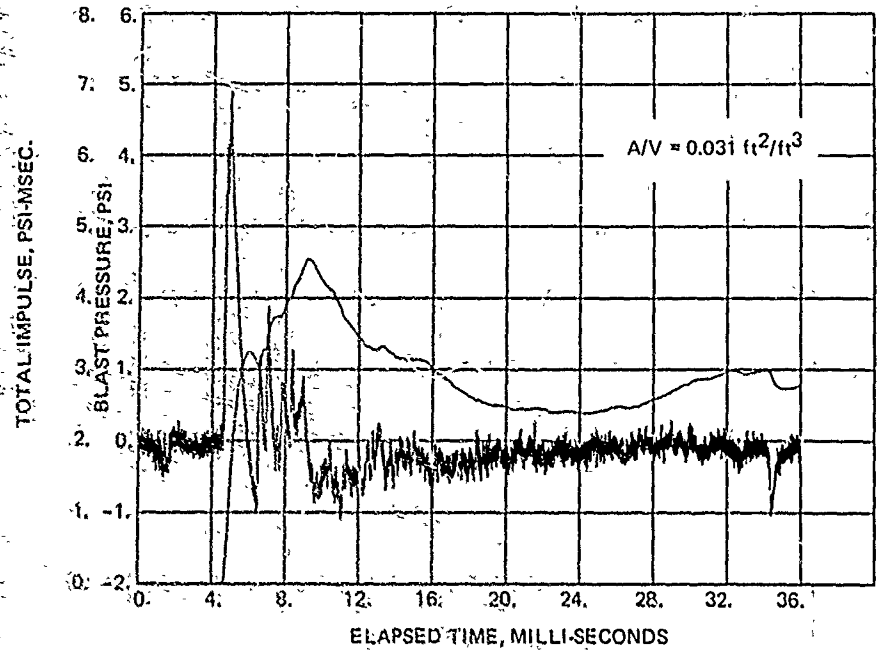
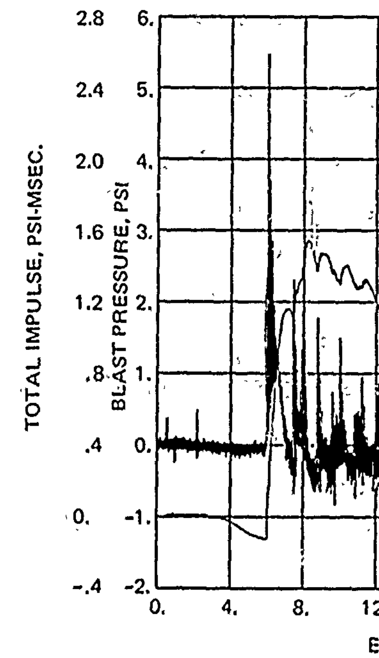


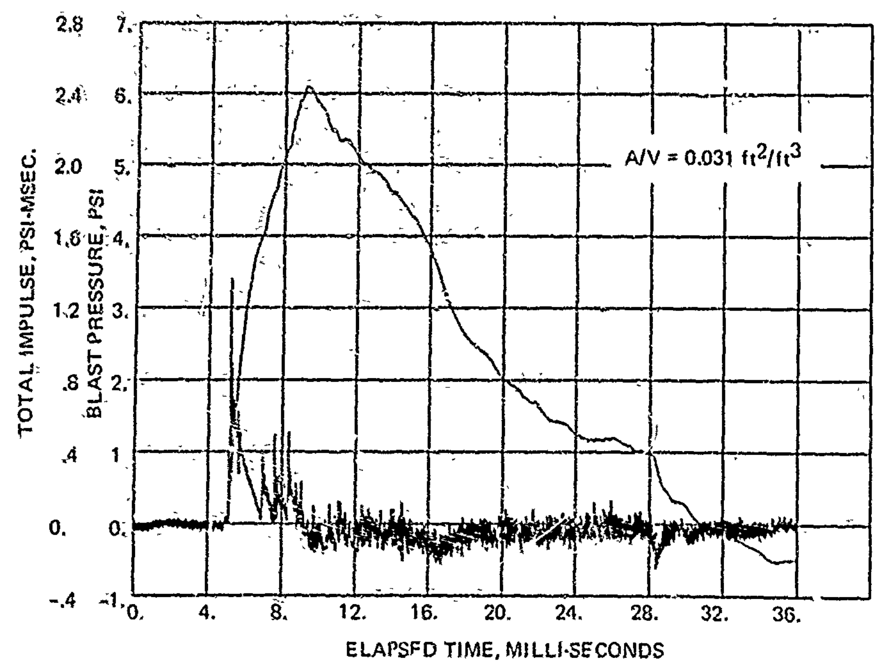
Figure A-8. Blast environment o

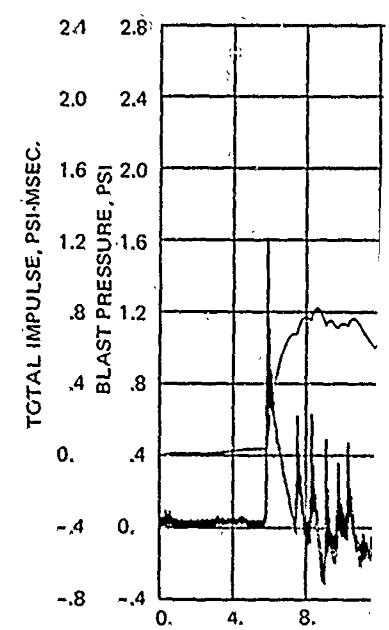




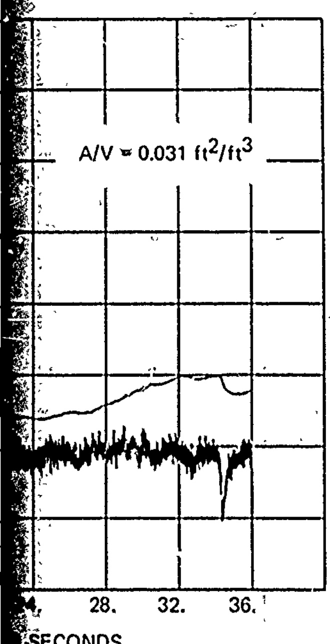


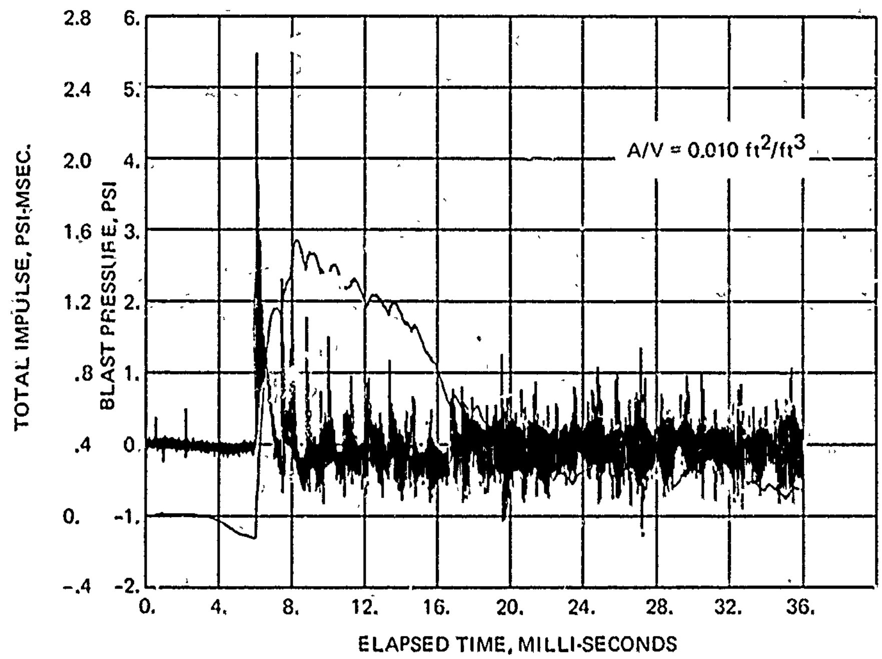
Blast environment outside 4-wall cubicles: explosive charges of 1.0 pound; various degrees of venting; Z = 8.00 ft/lb$^{1/3}$.



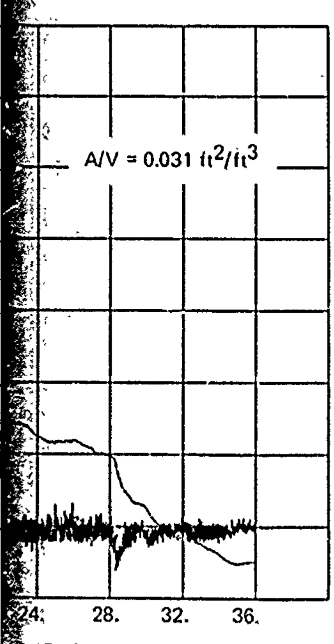


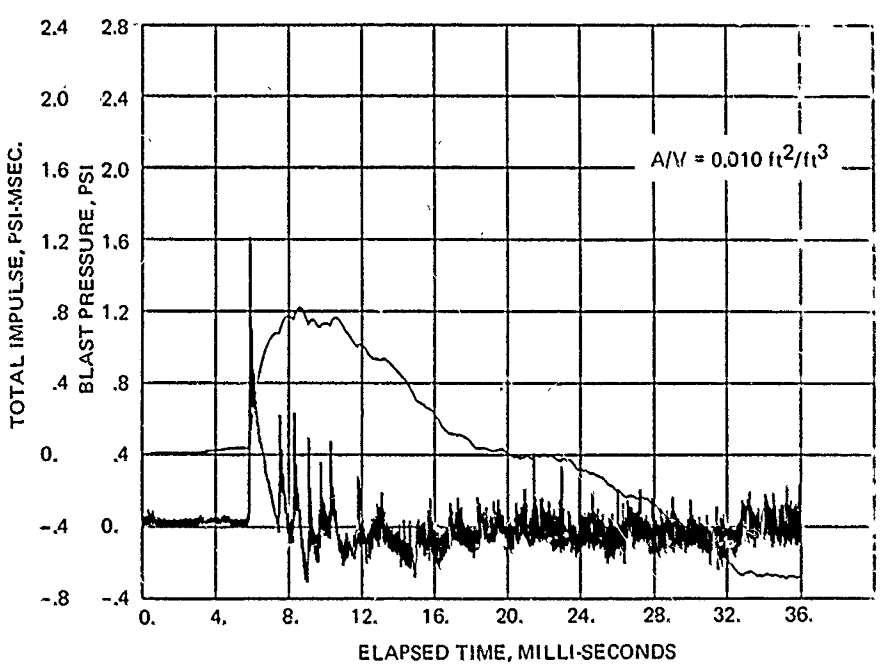
Blast environment outside 4-wall cubicles: explosive charges of 1.0 pound; various degrees of venting; Z = 16.0 ft/lb$^{1/3}$.



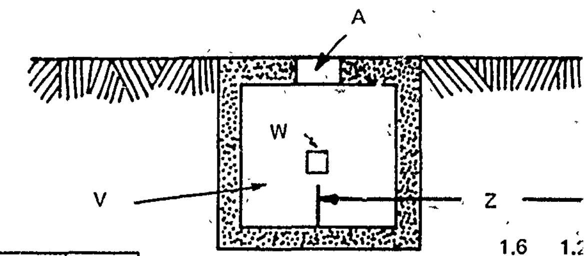


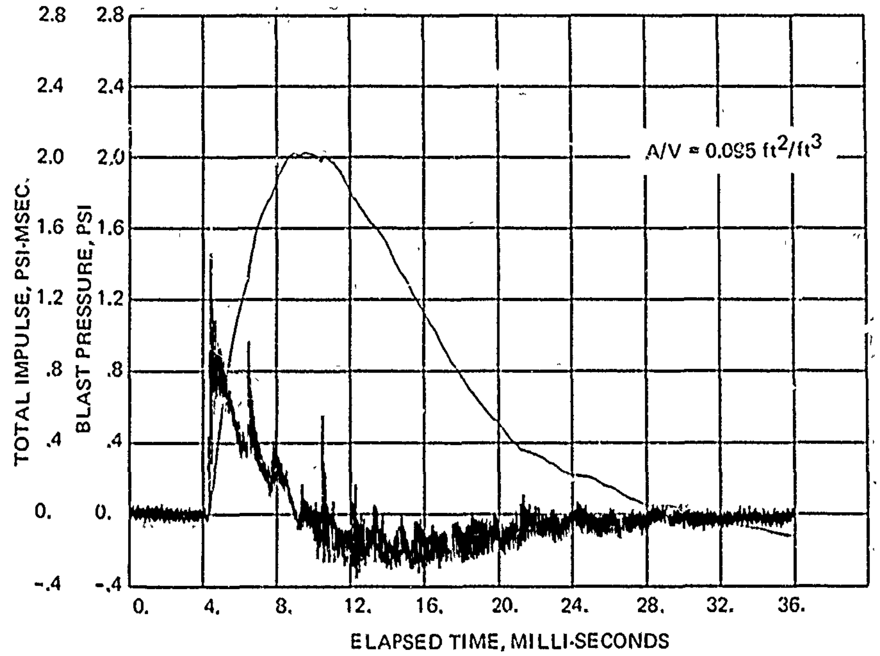
of 1.0 pound; various degrees of venting; $Z = 8.00$ ft/lb$^{1/3}$.





1.0 pound; various degrees of venting; $Z = 16.0$ ft/lb$^{1/3}$.





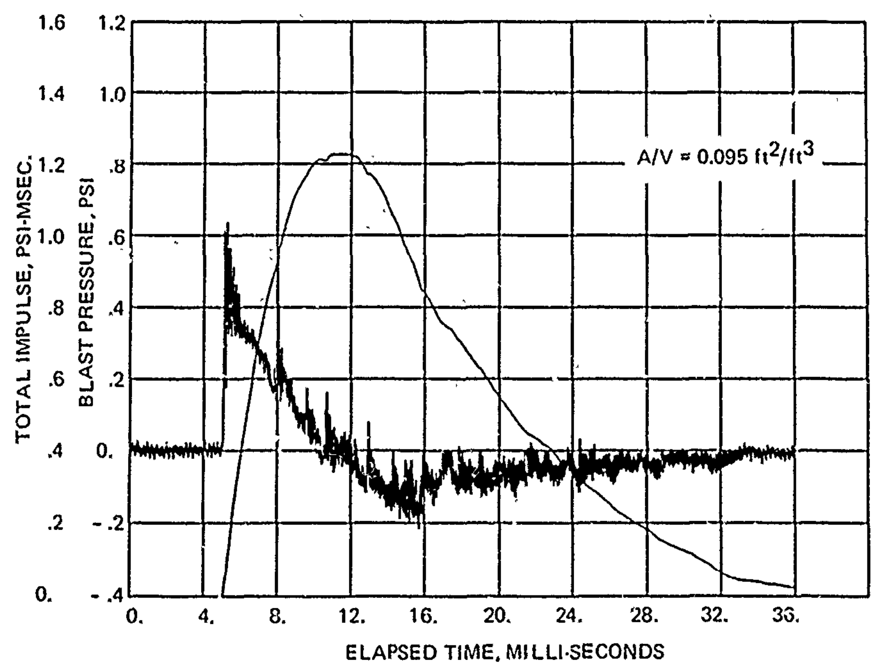
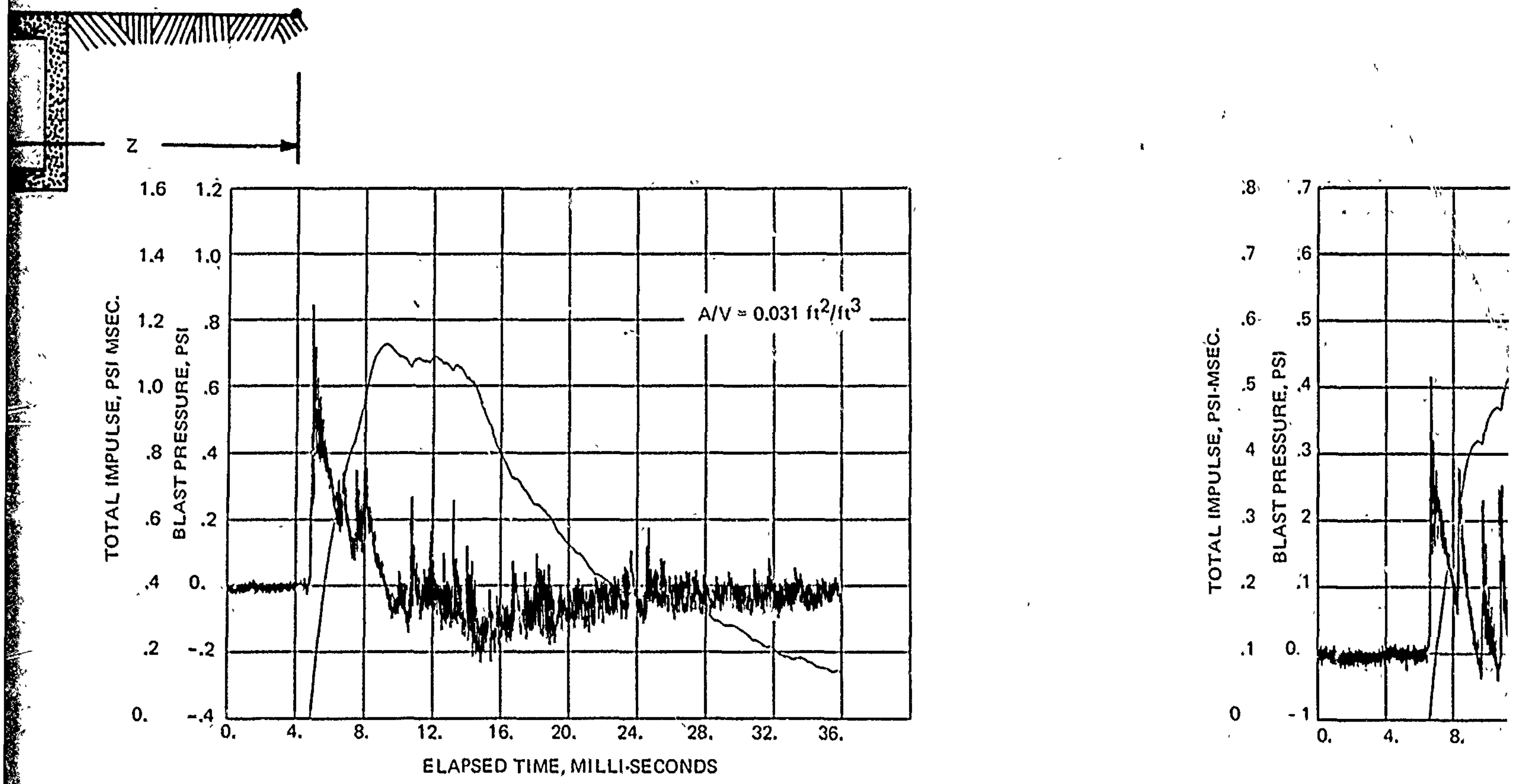
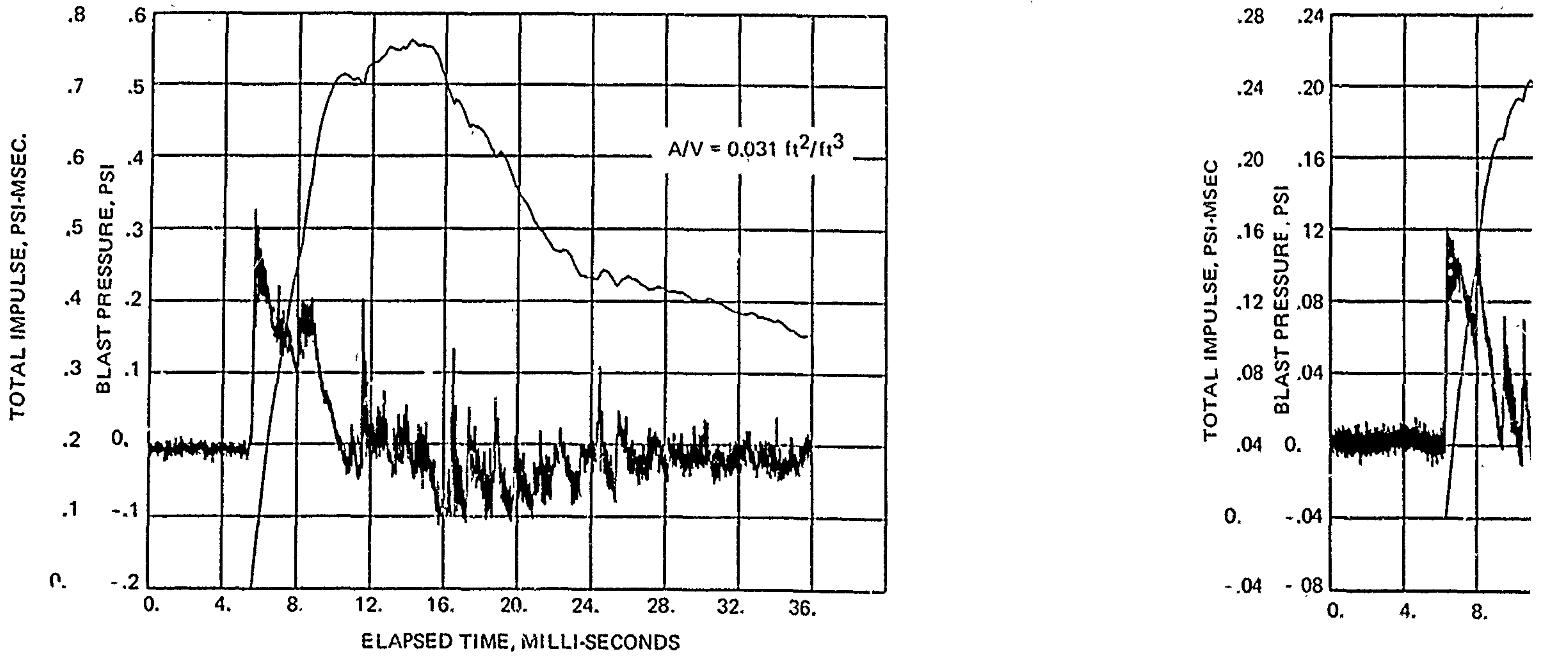


Figure A-9. Blast environment

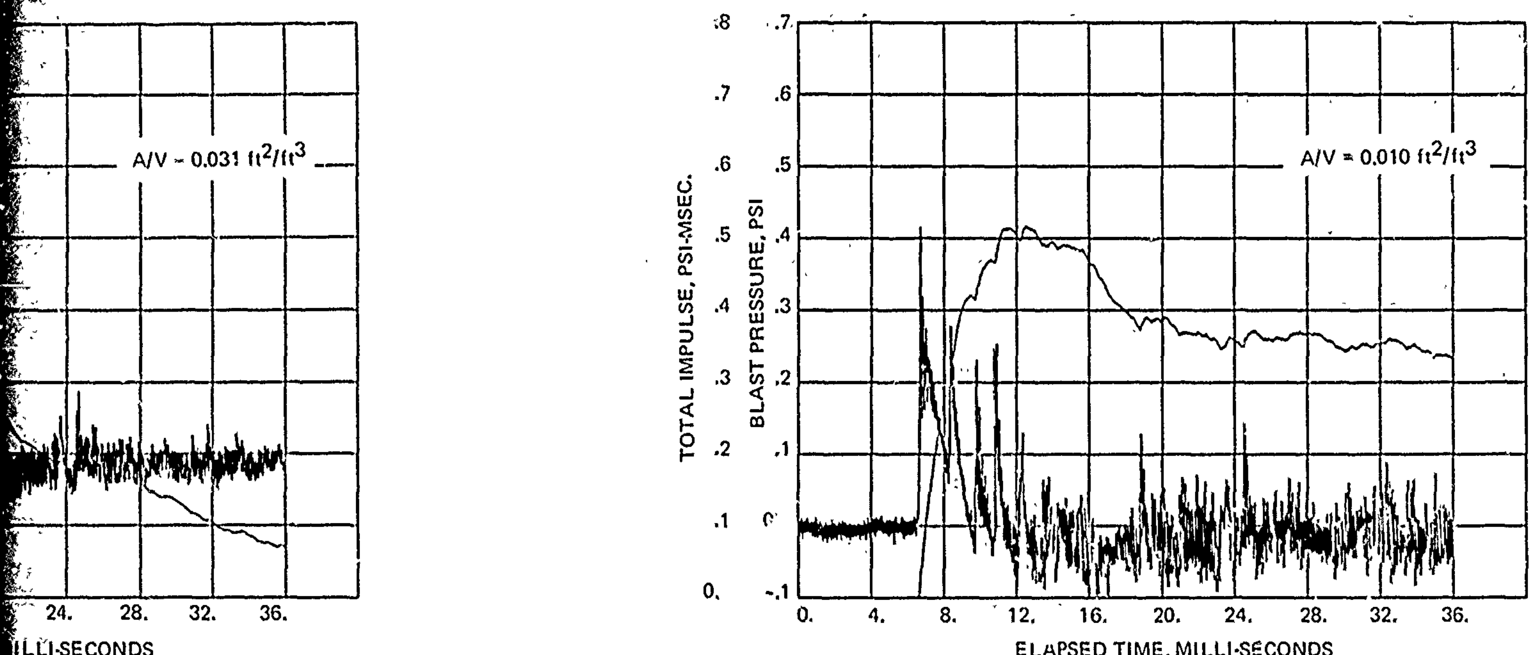
Figure A-10. Blast environment



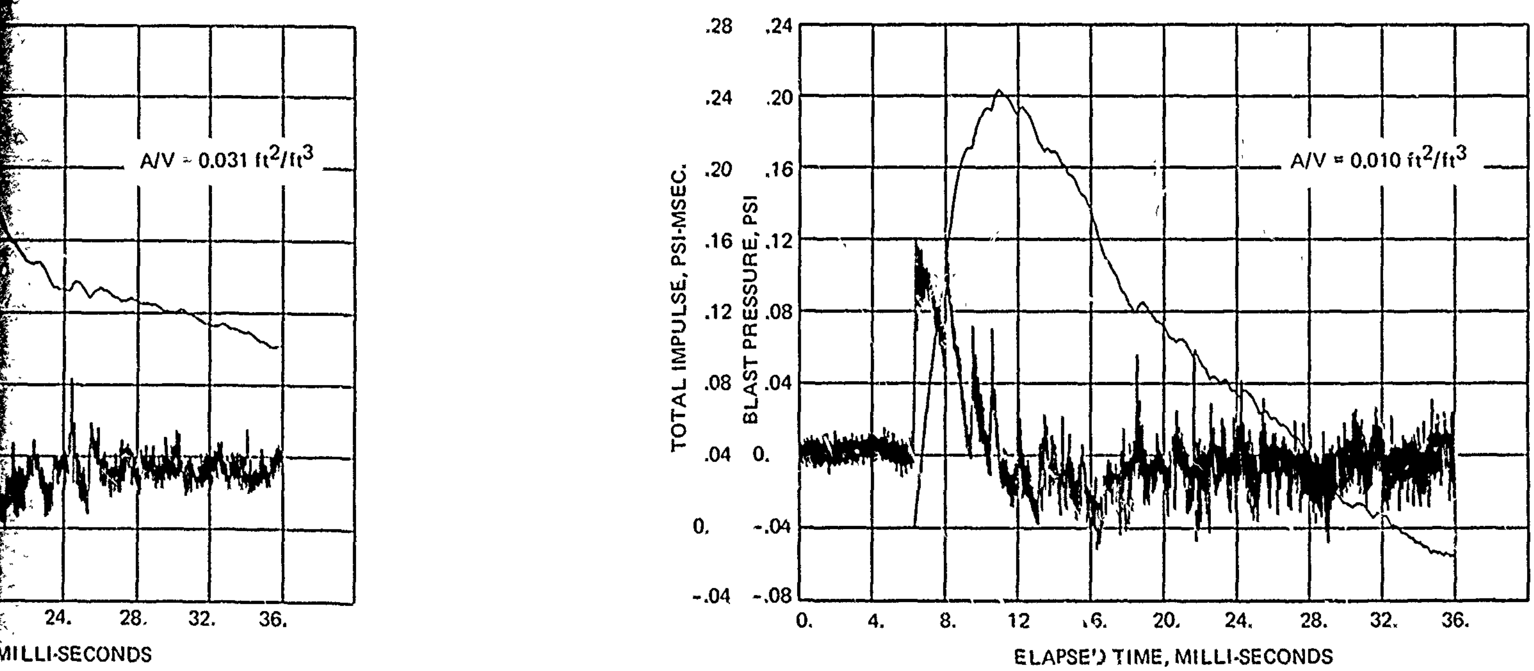
9. Blast environment outside 4-wall cubicles. explosive charges of 1.0 pound, various degrees of venting, Z = 32 ft/lb$^{1/3}$.



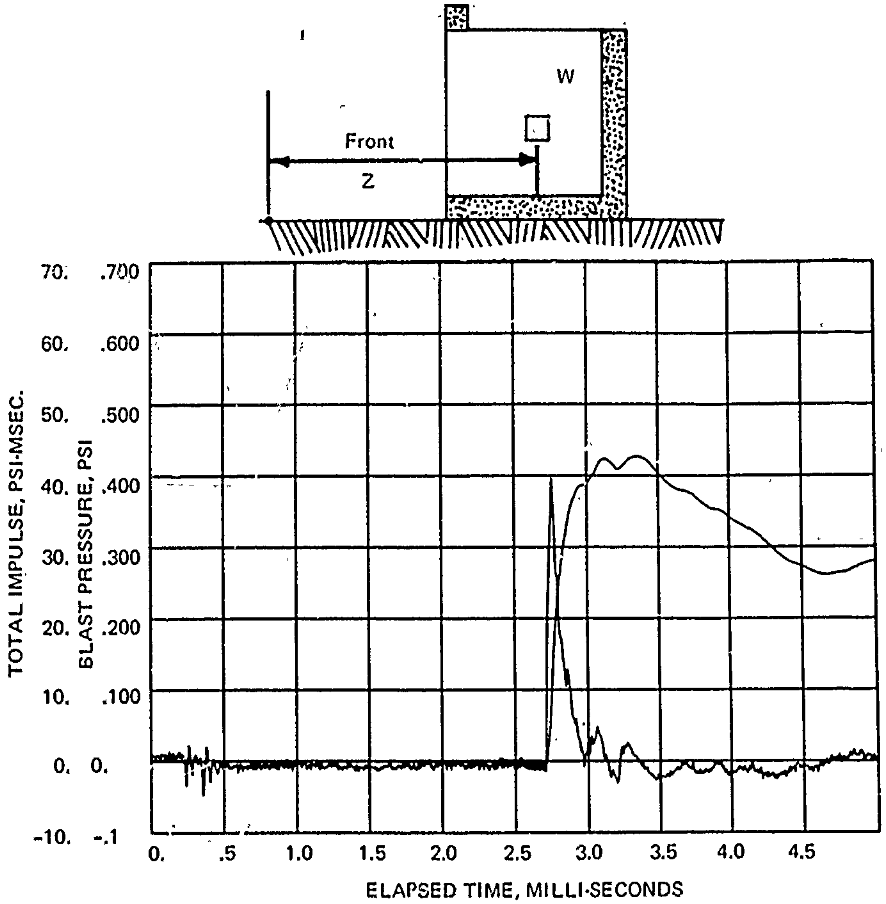
10. Blast environment outside 4-wall cubicles. explosive charges of 1.0 pound, various degrees of venting, Z - 50 ft/lb$^{1/3}$.

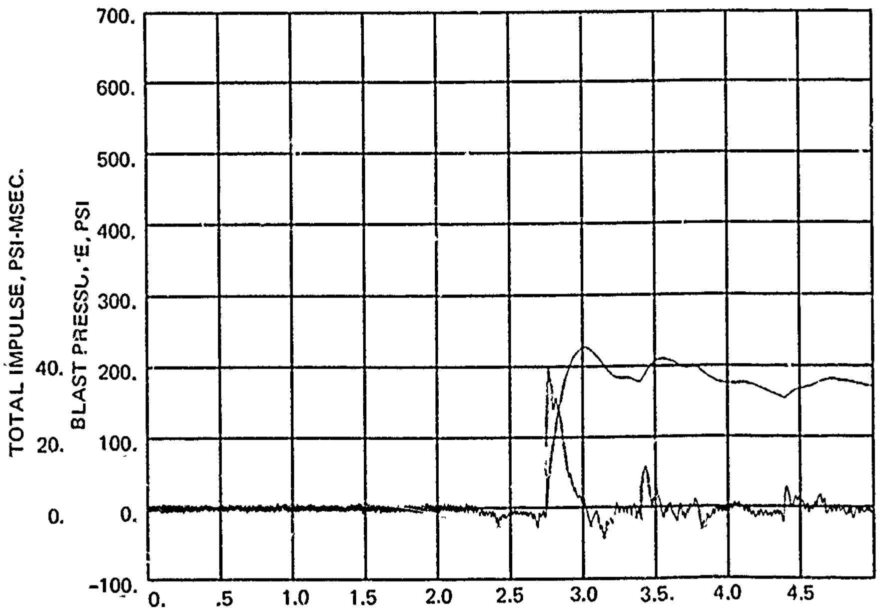


es of 1.0 pound; various degrees of venting; $Z \approx 32$ ft/lb$^{1/3}$.



rges of 1.0 pound; various degrees of venting; $Z = 50$ ft/lb$^{1/3}$.





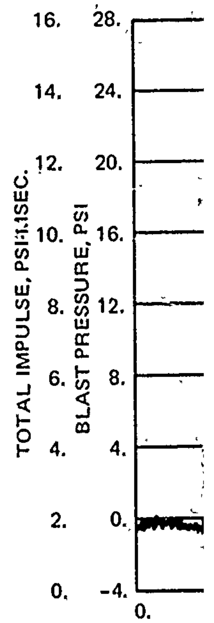


Figure A-11. Blast environmen

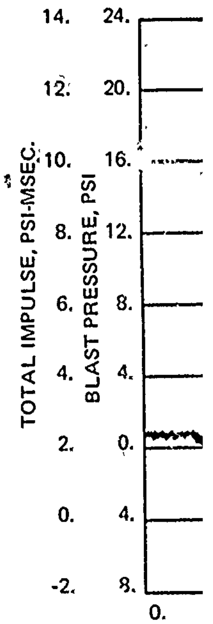
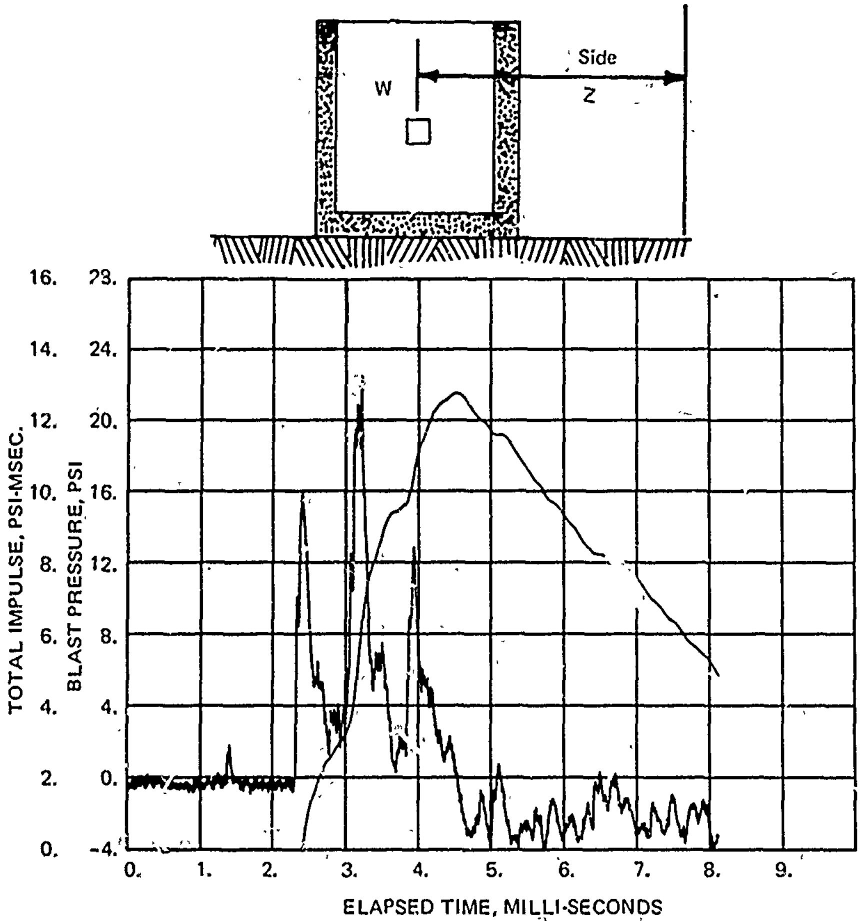
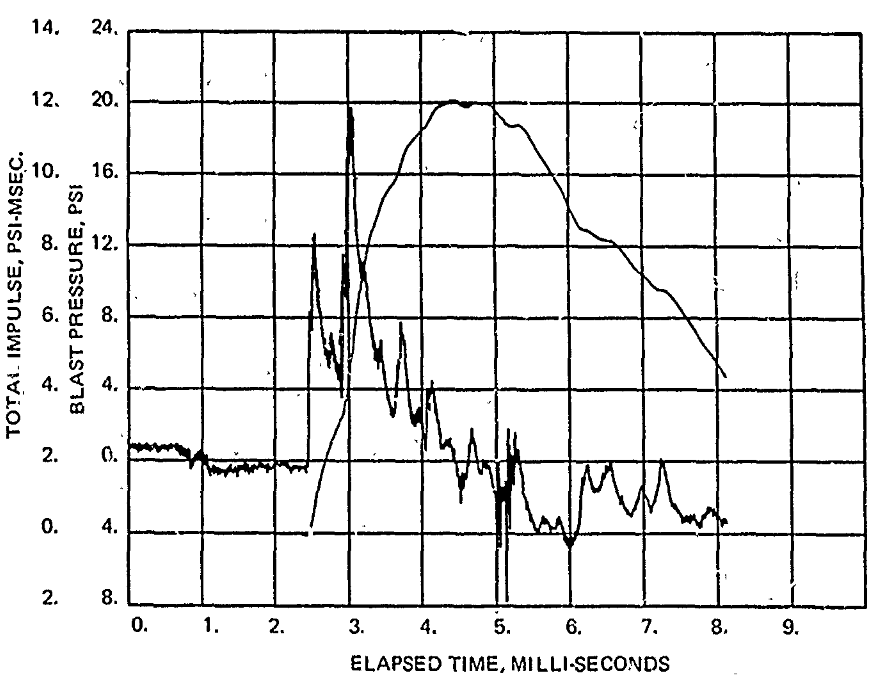


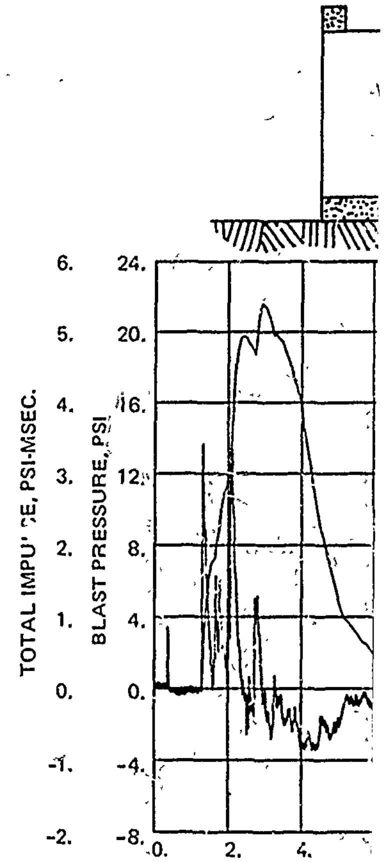
Figure A-12. Blast environment out

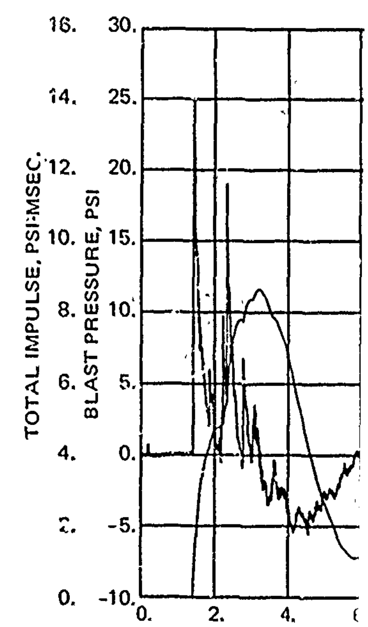


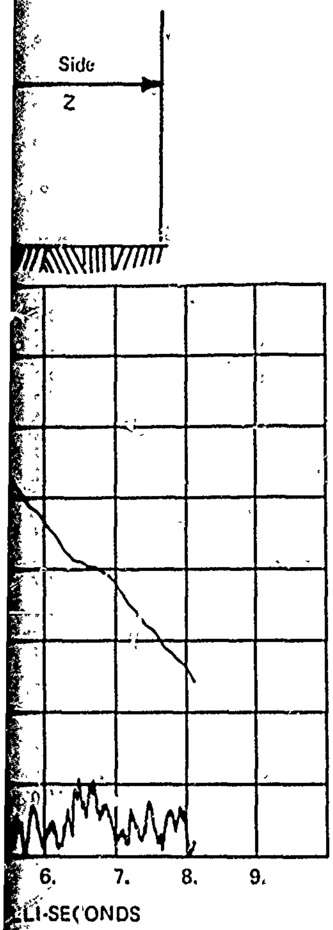
A-11. Blast environment outside small 3-wall cubicle without roof; explosive charges of 1.0 pound; Z = 2.0 ft/lb$^{1/3}$.

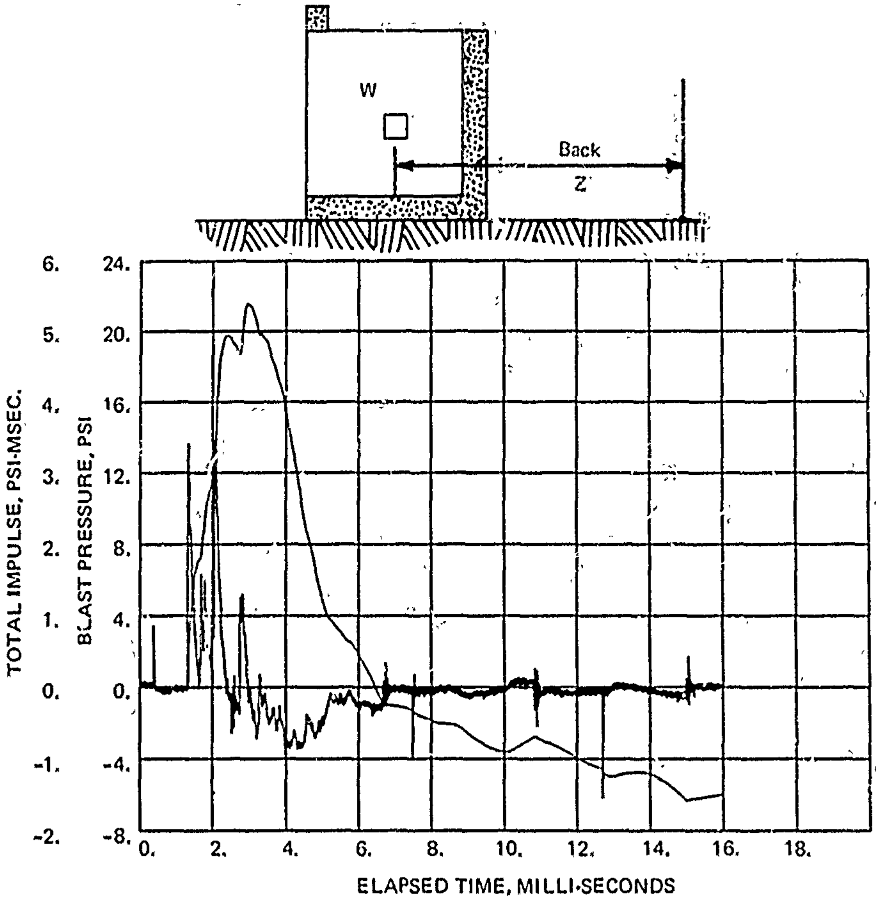


12. Blast environment outside small 3-wall cubicle without roof. explosive charges of 1.0 pound, Z = 4.0 ft/lb$^{1/3}$.

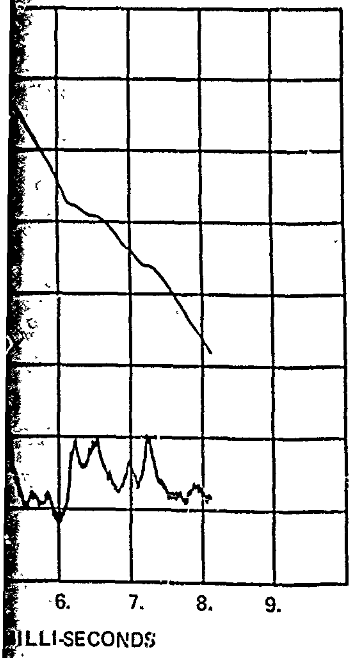


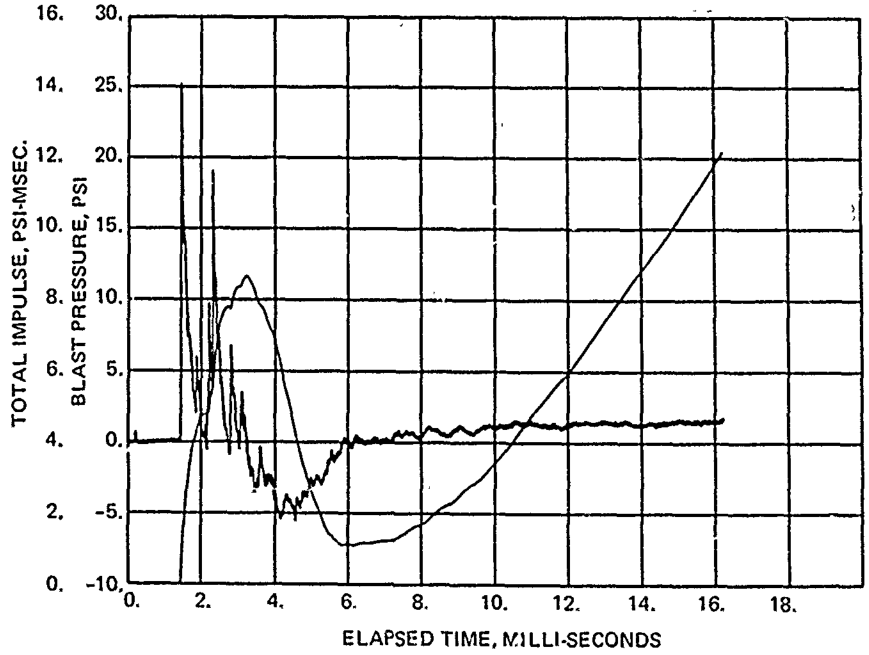






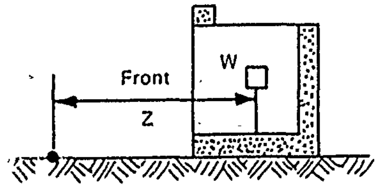
our roof: explosive charges of 1.0 pound; Z = 2.0 ft/lb$^{1/3}$.

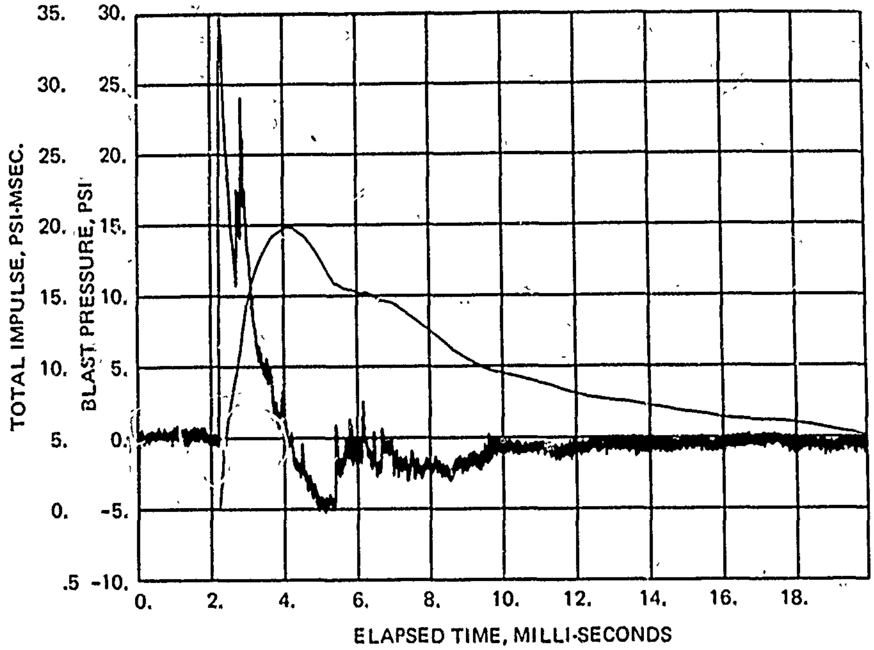


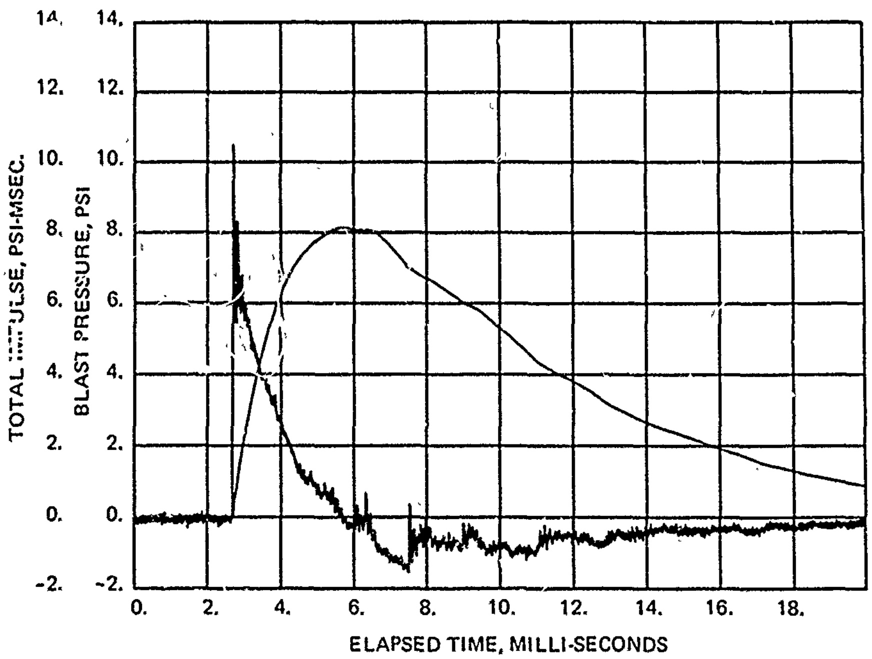


roof: explosive charges of 1.0 pound; Z = 4.0 ft/lb$^{1/3}$.

3







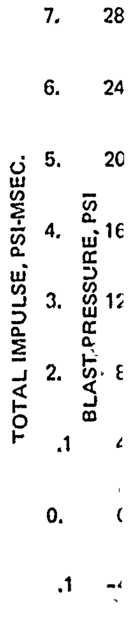


Figure A-13. Blast environm

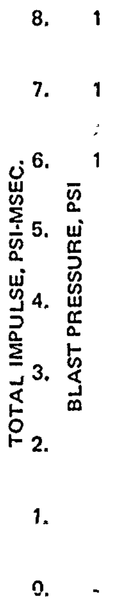
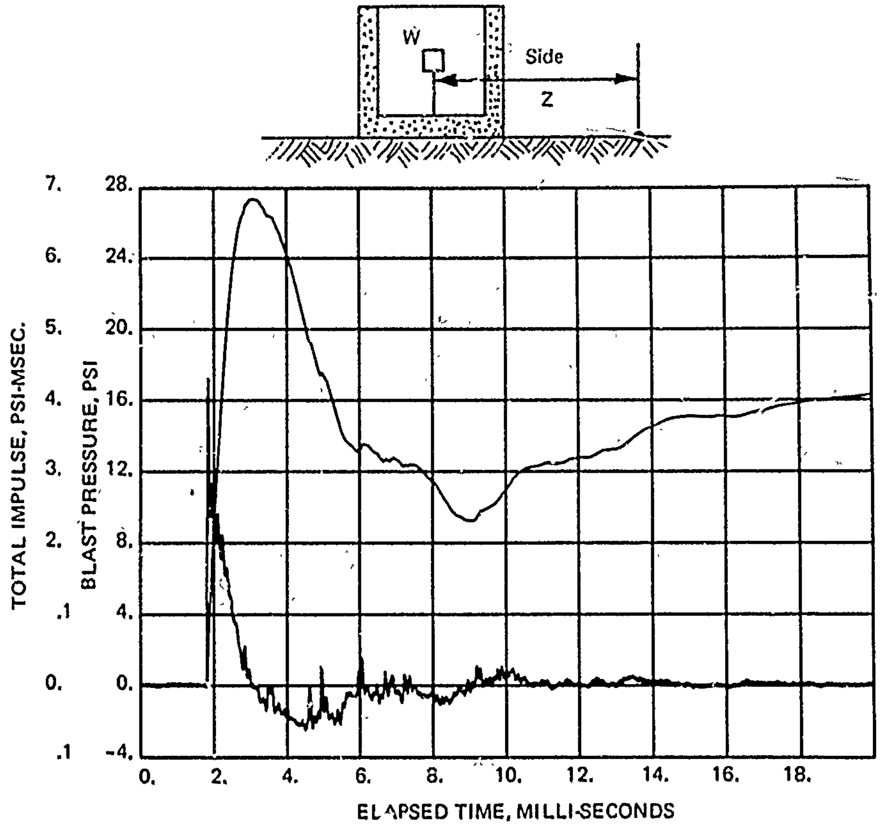
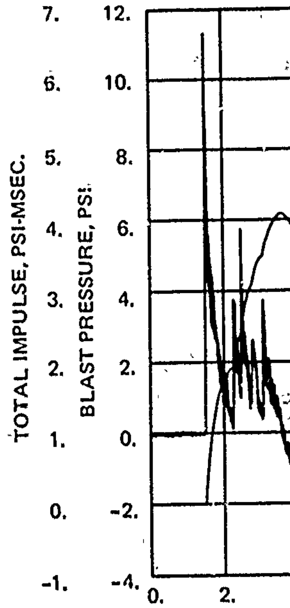
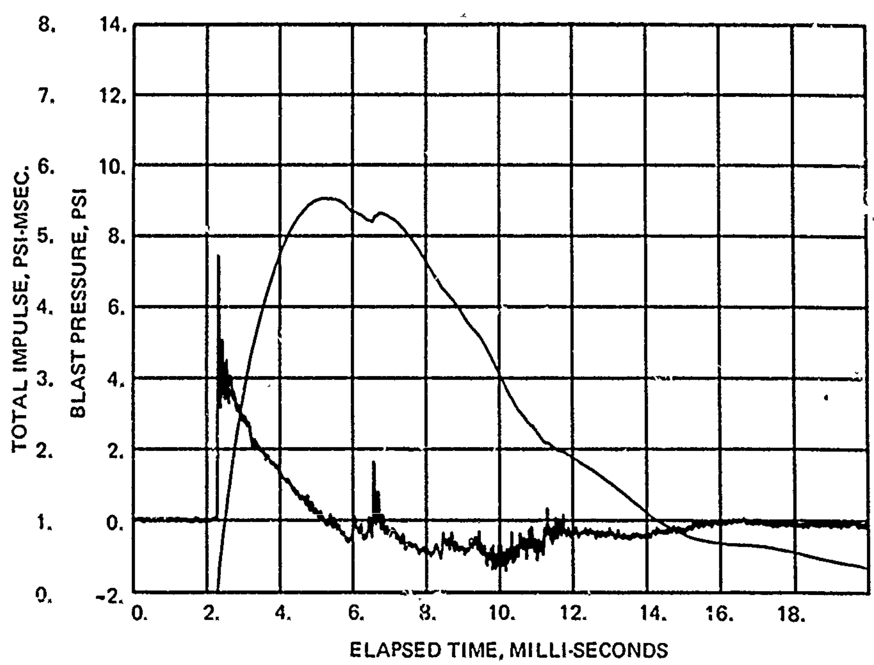


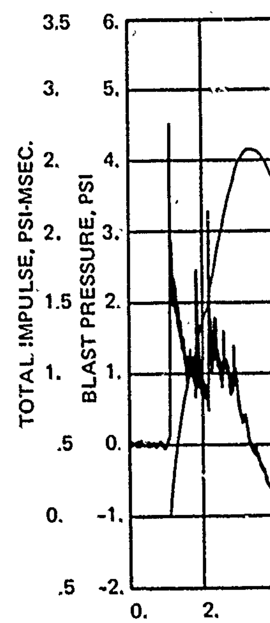
Figure A-14. Blast enviro





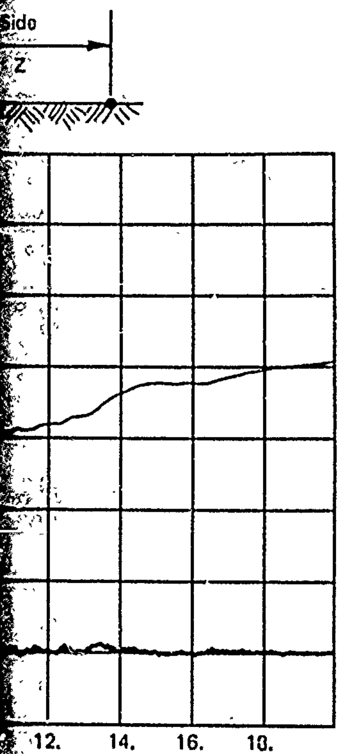
re A-13. Blast environment outside small 3-wall cubicle without roof. explosive charges of 1.0 pound, $Z = 8.0$ ft/lb$^{1/3}$.

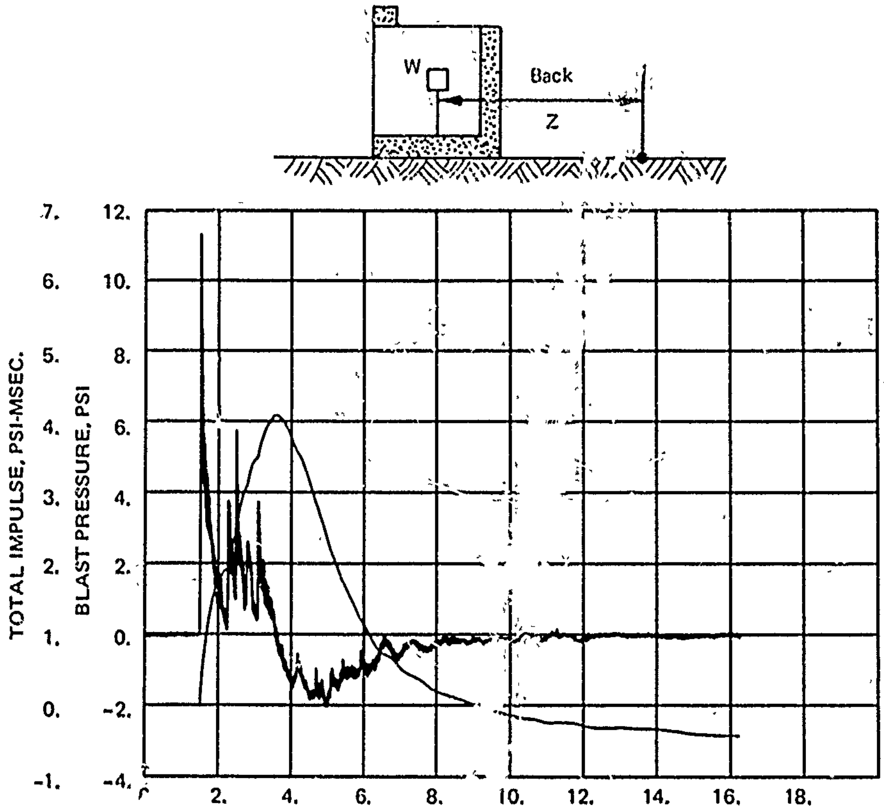




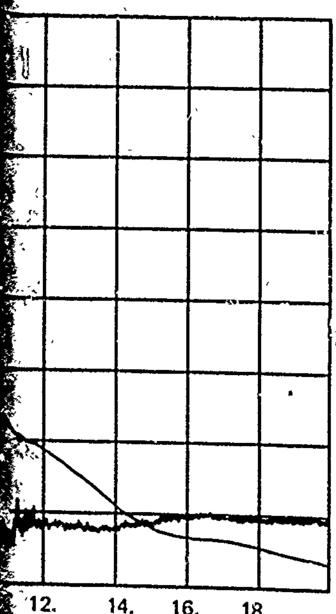
gure A 14. Blast environment outside small 3 wall cubicle without roof. explosive charges of 1.0 pound, $Z = 16.0$ ft/lb$^{1/3}$.

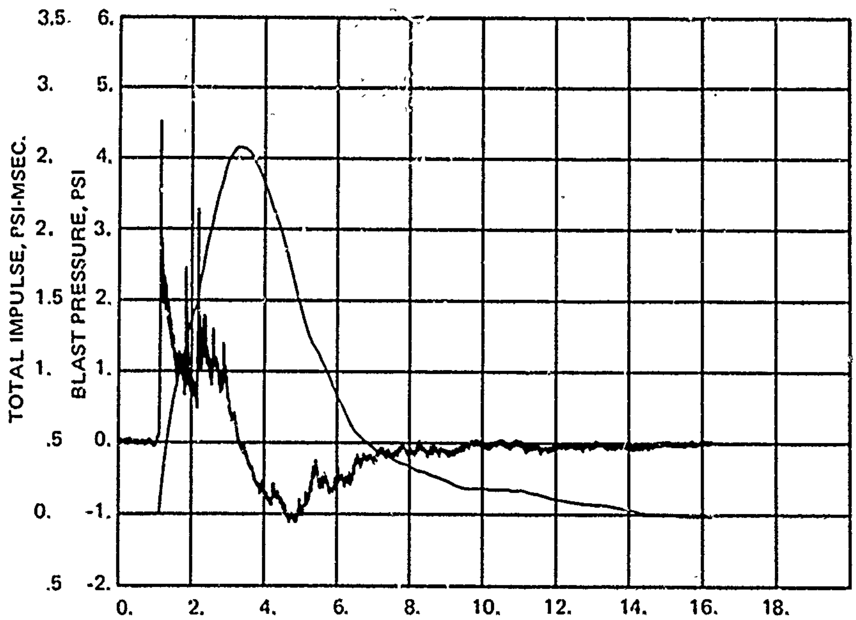
2





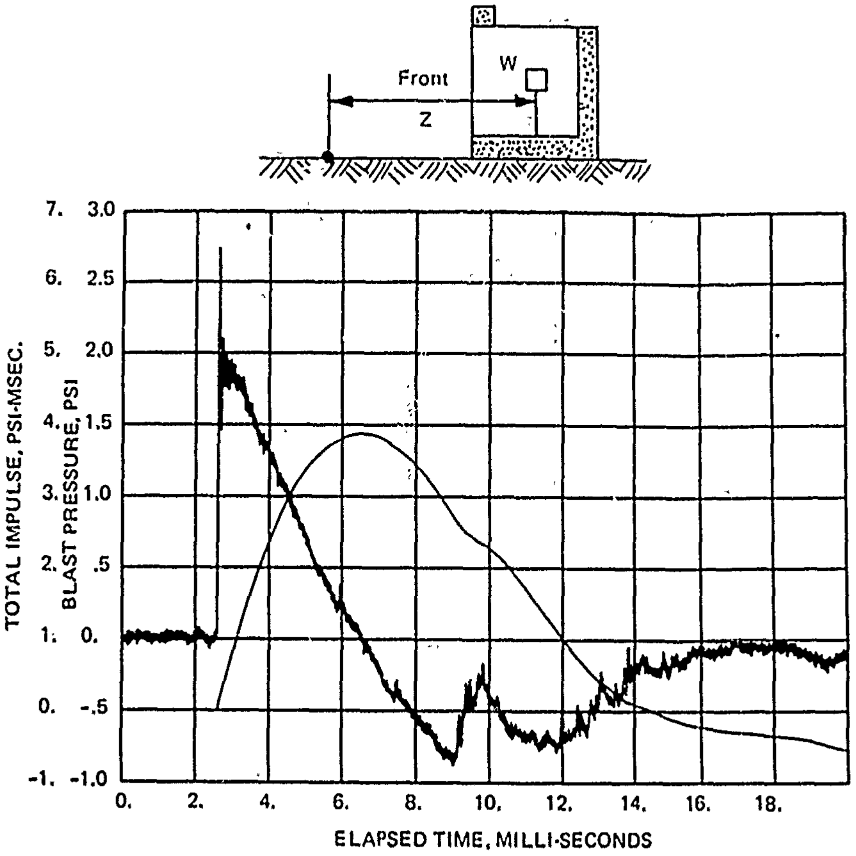
oof: explosive charges of 1.0 pound; Z = 8.0 ft/lb$^{1/3}$.

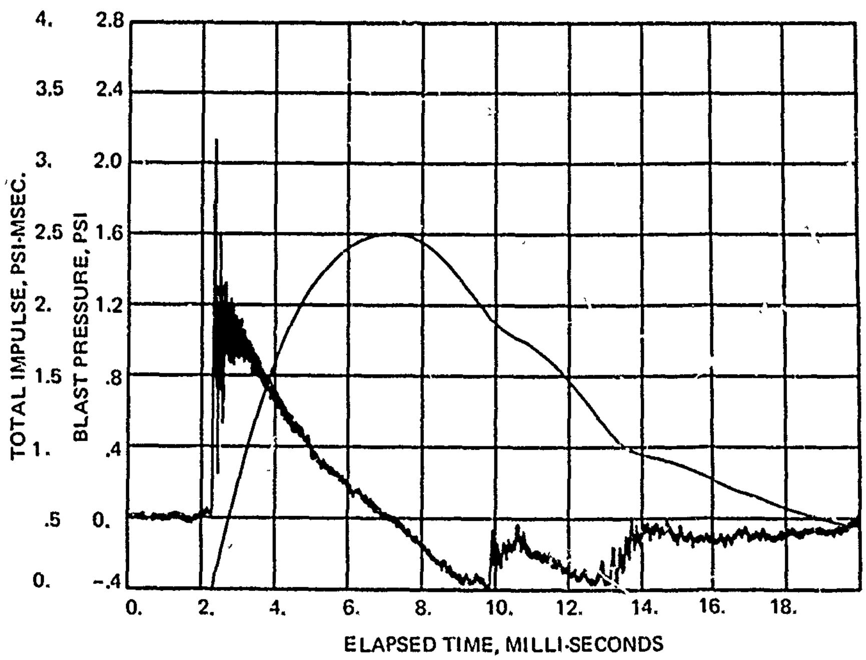




oof: explosive charges of 1.0 pound; Z = 16.0 ft/lb$^{1/3}$.

3





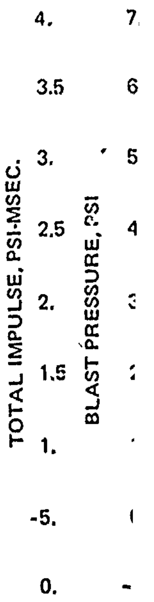


Figure A-15. Blast envi

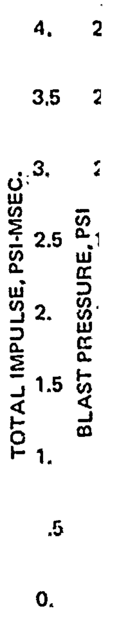
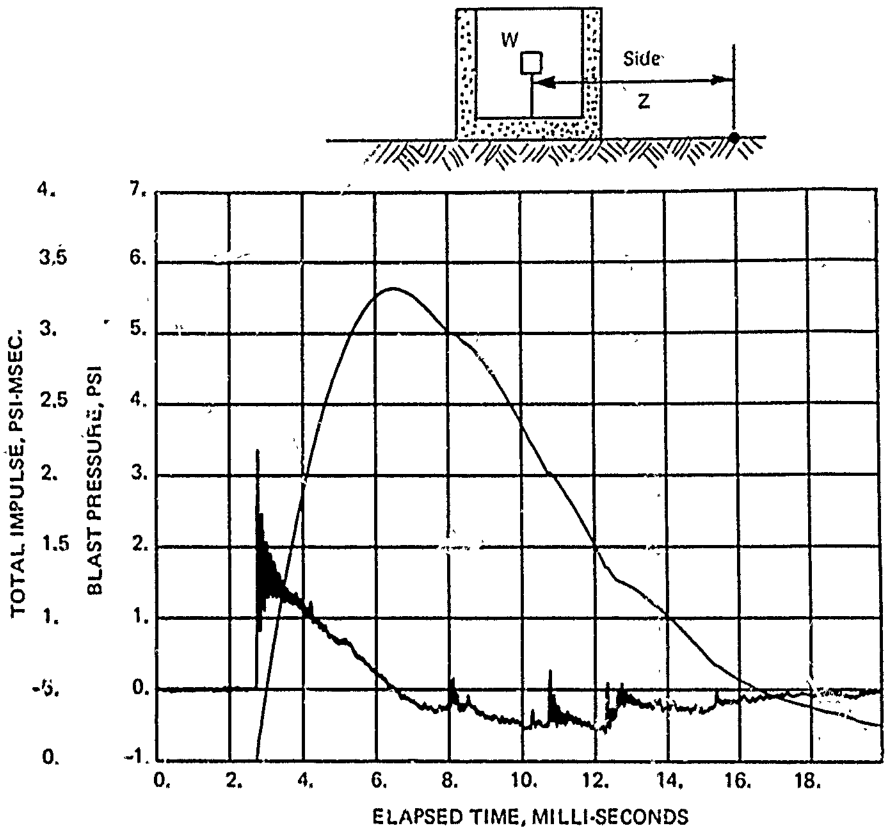


Figure A-16. Blast env



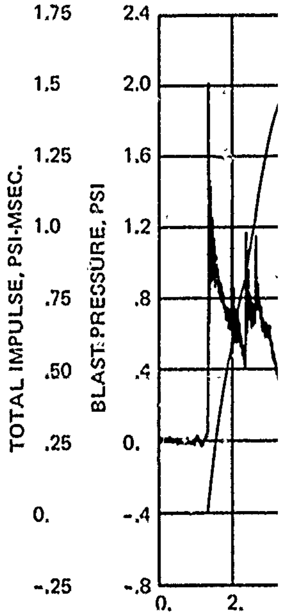
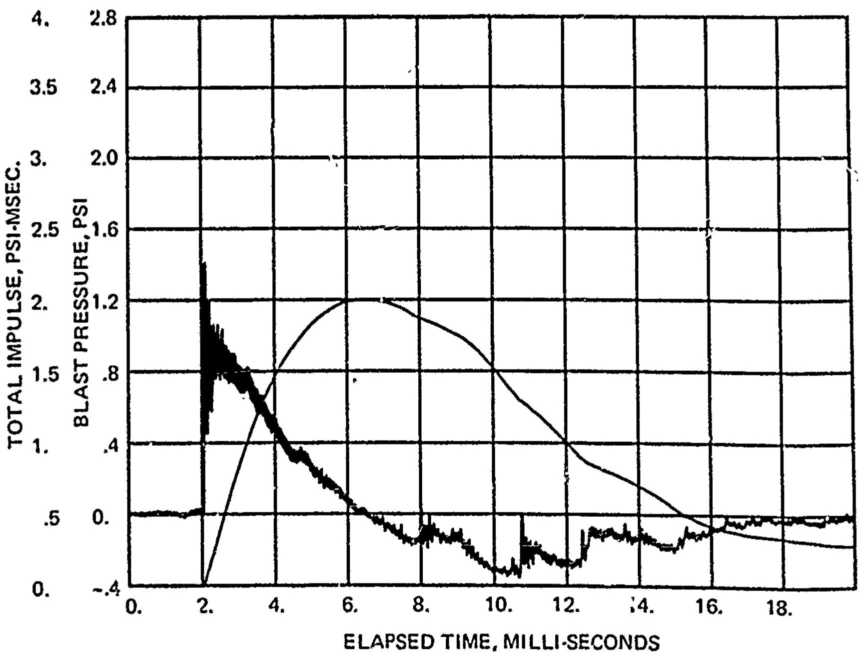


Figure A 15. Blast environment outside small 3 wall cubicle without roof. explosive charges of 1.0 pound, Z = 32 ft/lb$^{1/3}$.



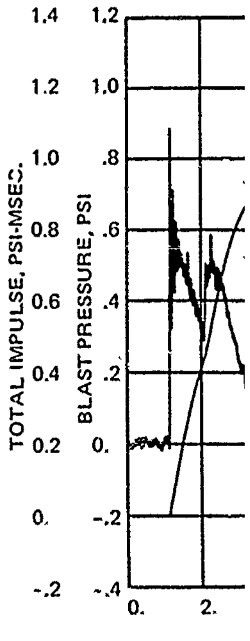
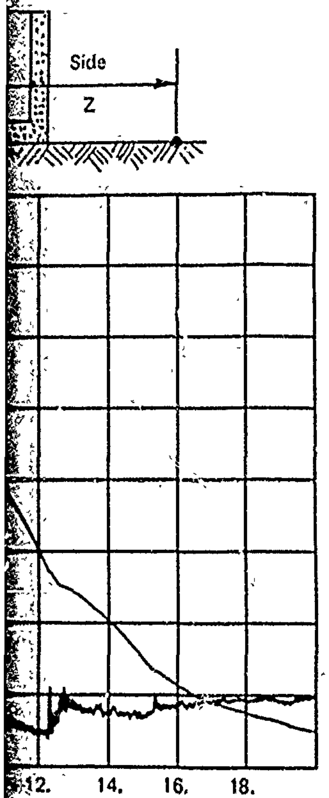
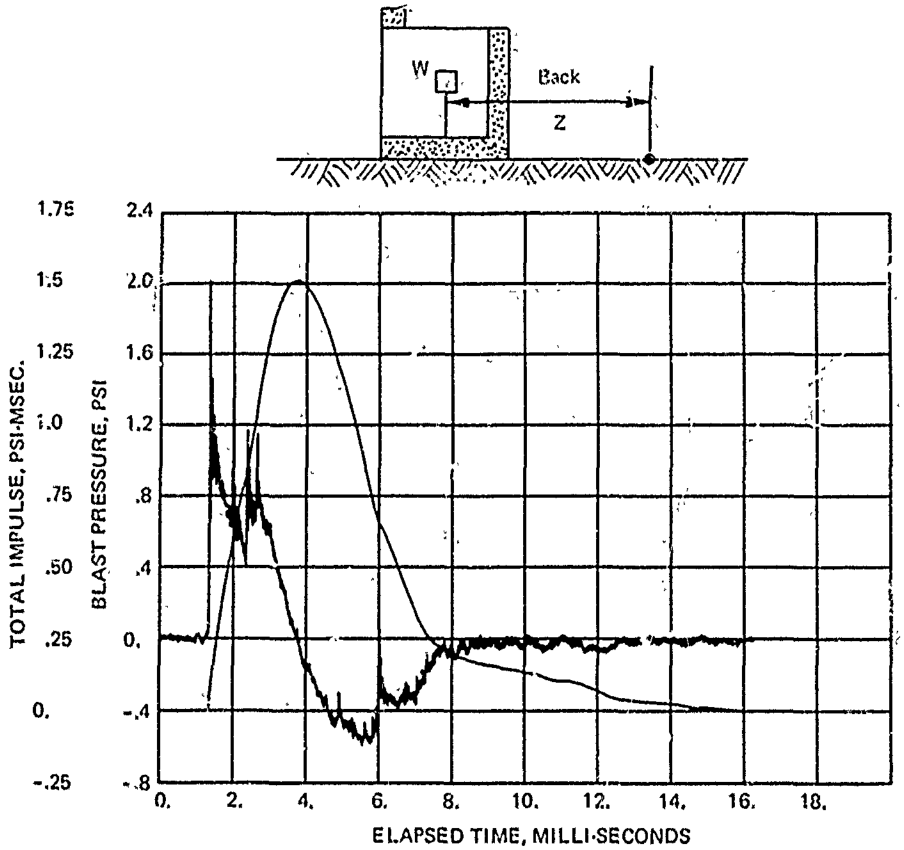
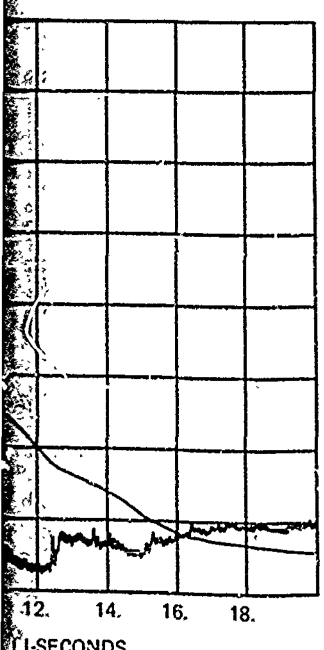


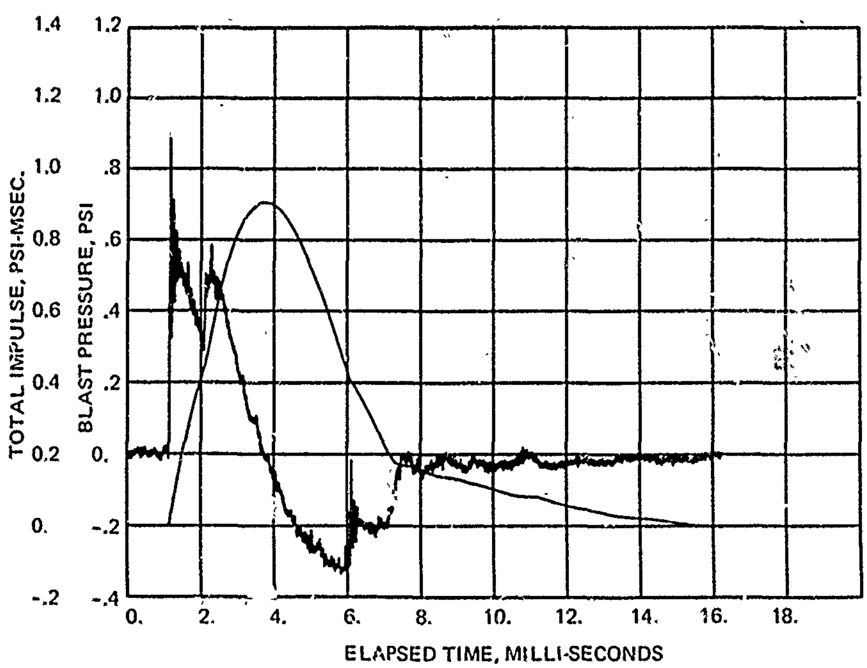
Figure A 16. Blast environment outside small 3 wall cubicle without roof. explosive charges of 1.0 pound, Z = 50 ft/lb$^{1/3}$





t roof: explosive charges of 1.0 pound; Z = 32 ft/lb$^{1/3}$.





r roof: explosive charges of 1.0 pound; Z = 50 ft/lb$^{1/3}$

3

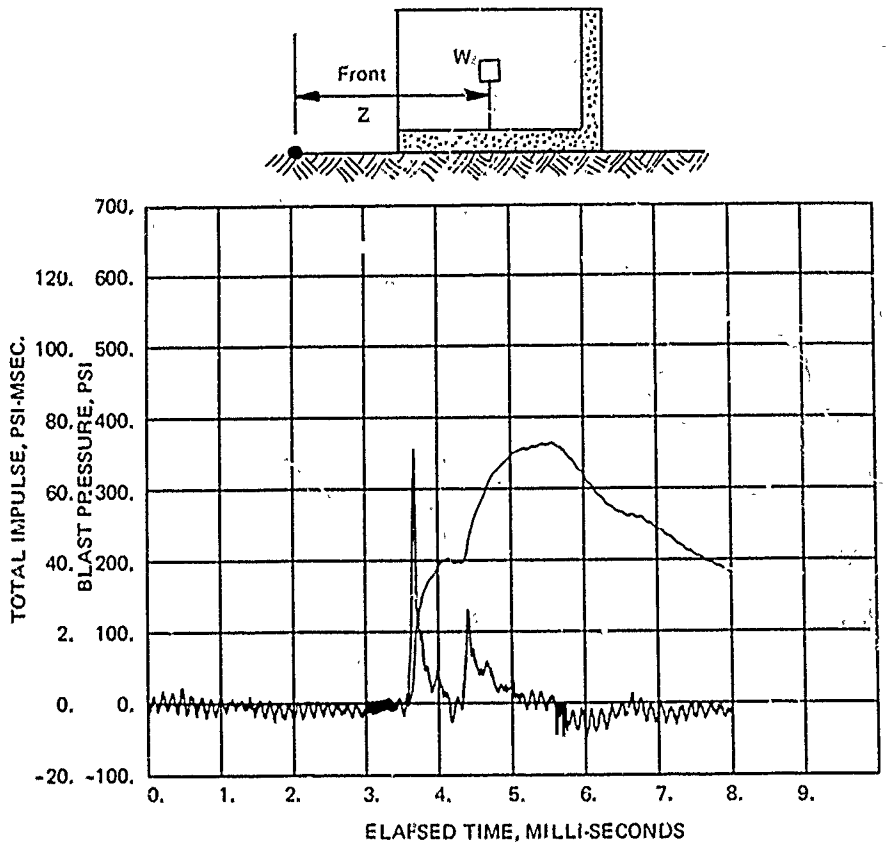
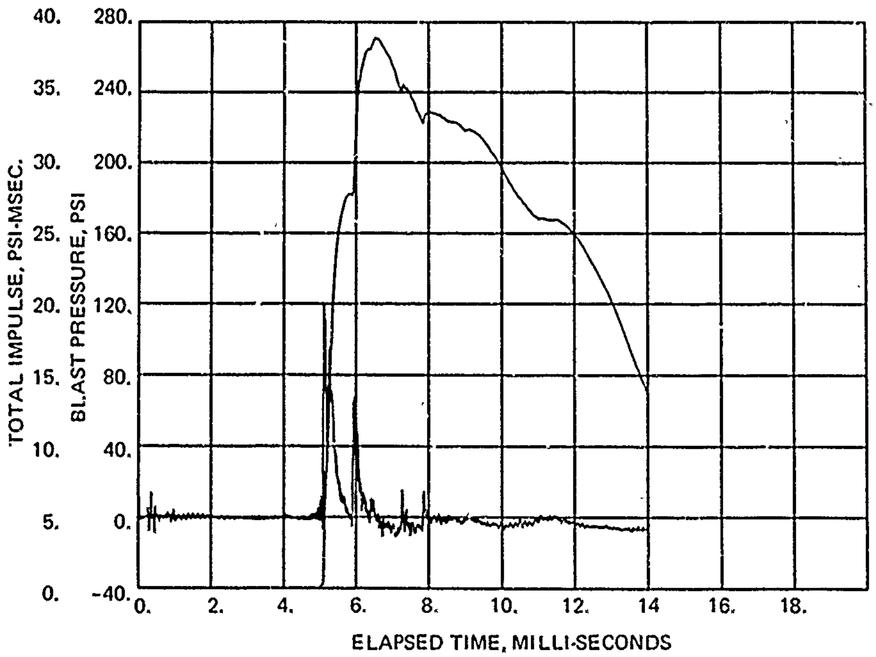


Figure A-17. Blast environm



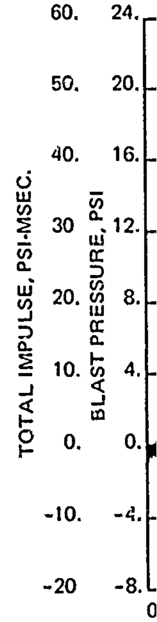
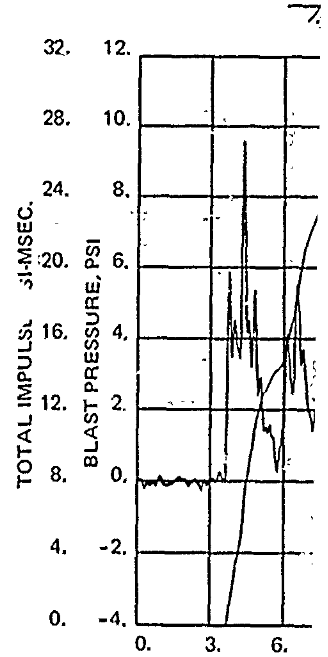
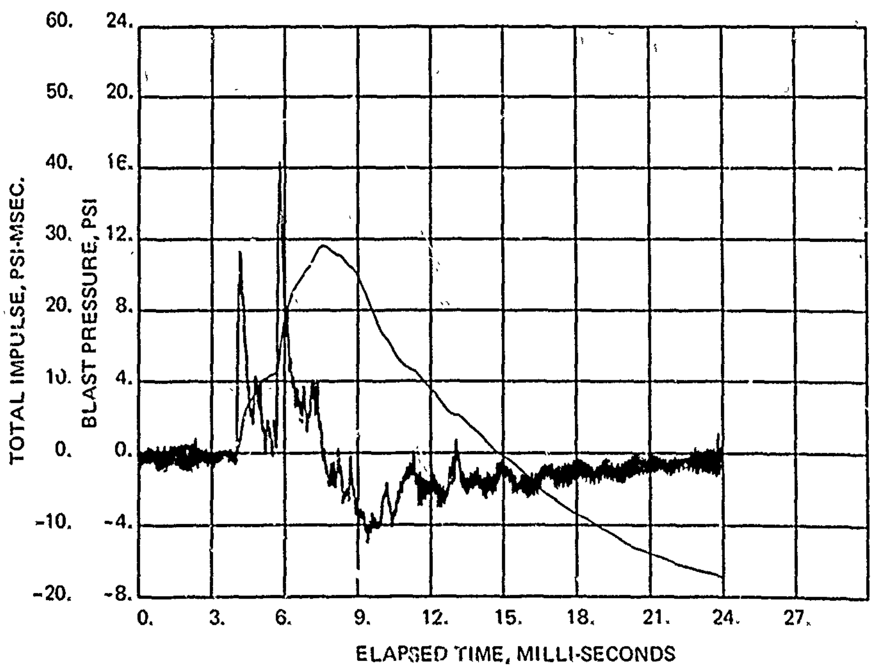
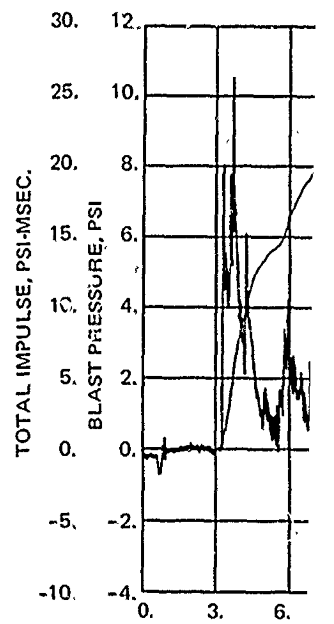


Figure A-18. Blast environment

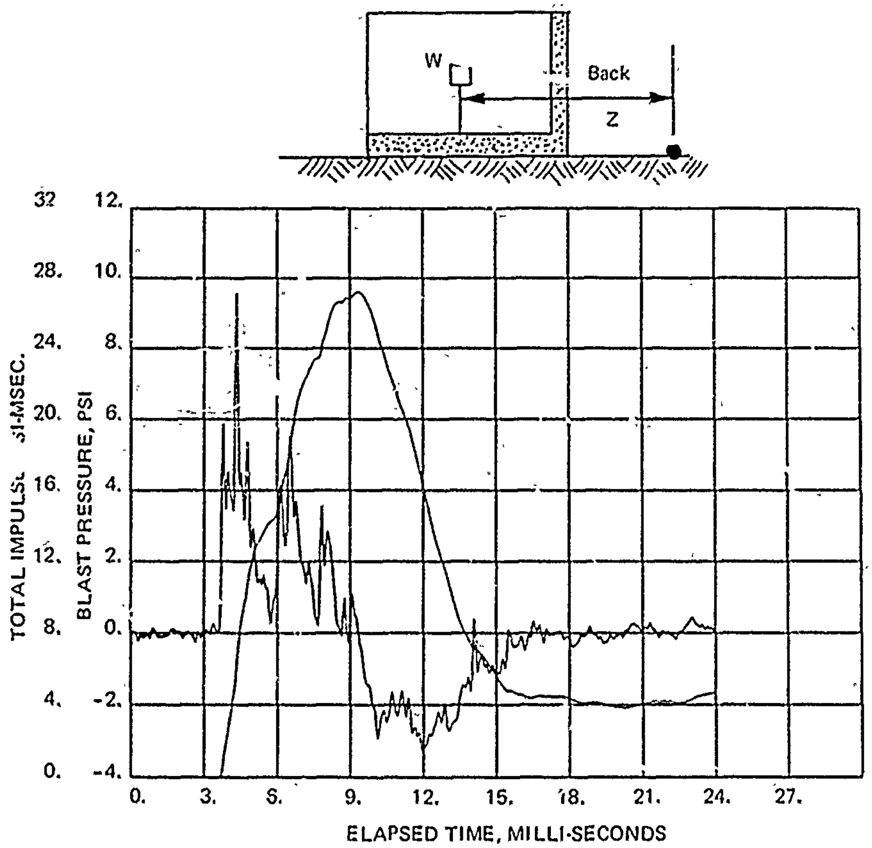


igure A-17. Blast environment outside large 3-wall cubicle without roof. explosive charge of 1.5 pounds, Z = 1.92 ft/lb$^{1/3}$.

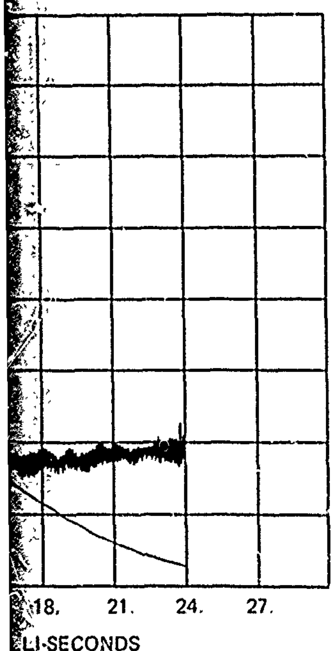


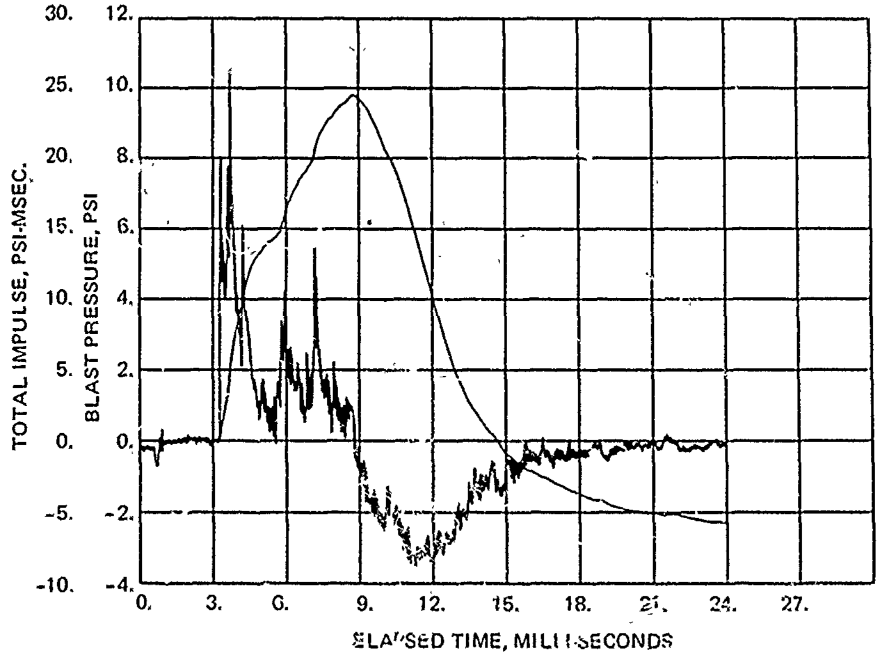


re A-18. Blast environment outside large 3-wall cubicle without roof: explosive charges of 1.5 pounds, Z = 3.49 ft/lb$^{1/3}$.



roof: explosive charges of 1.5 pounds; $Z = 1.92\ ft/lb^{1/3}$.





explosive charges of 1.5 pounds; $Z = 3.49\ ft/lb^{1/3}$.

3

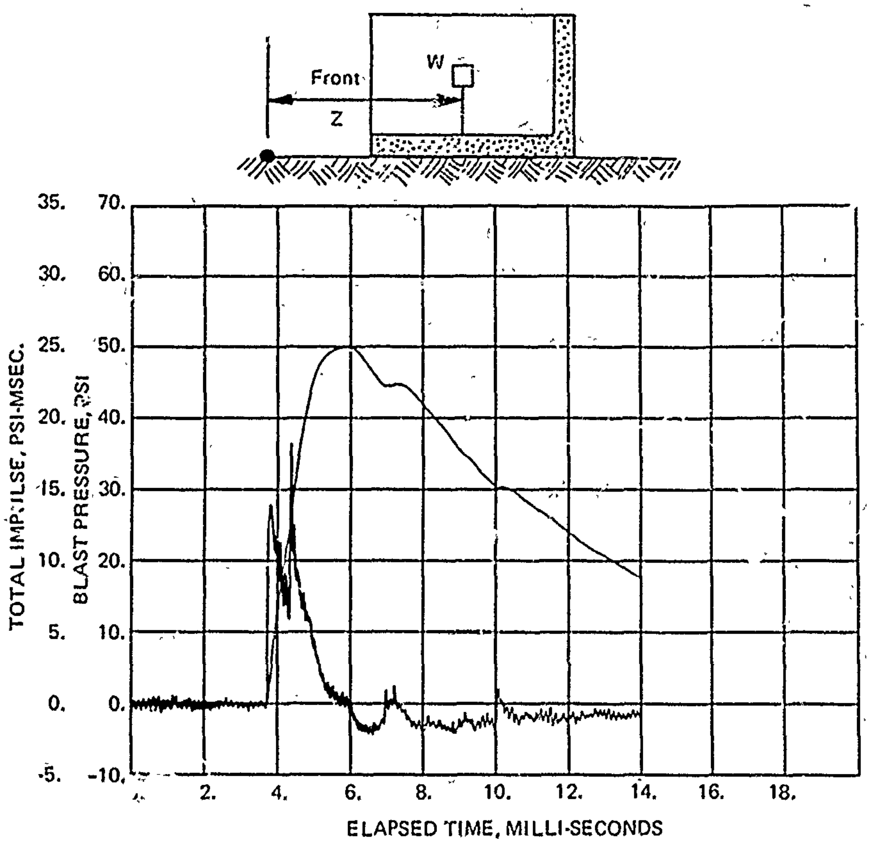


Figure A-19. Blast environn

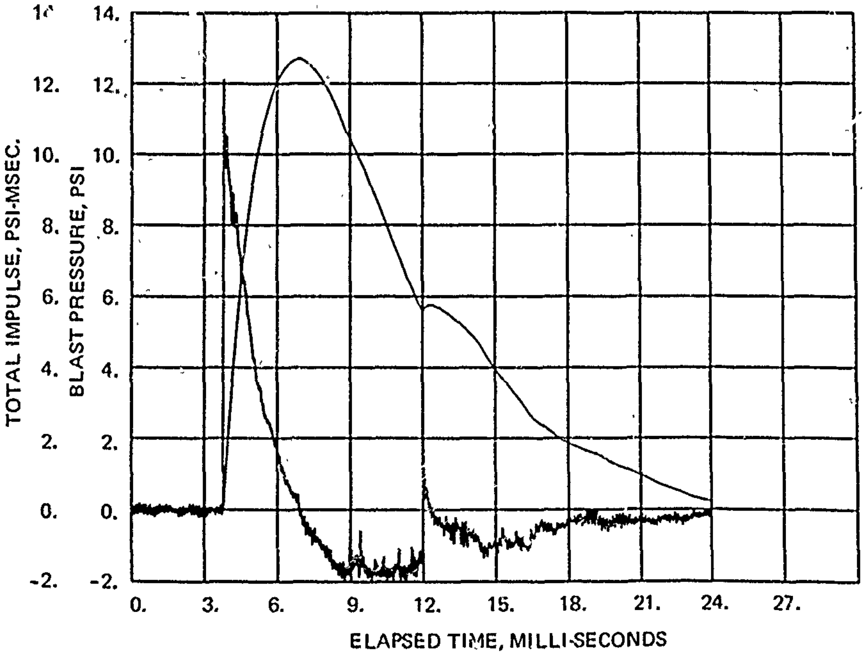
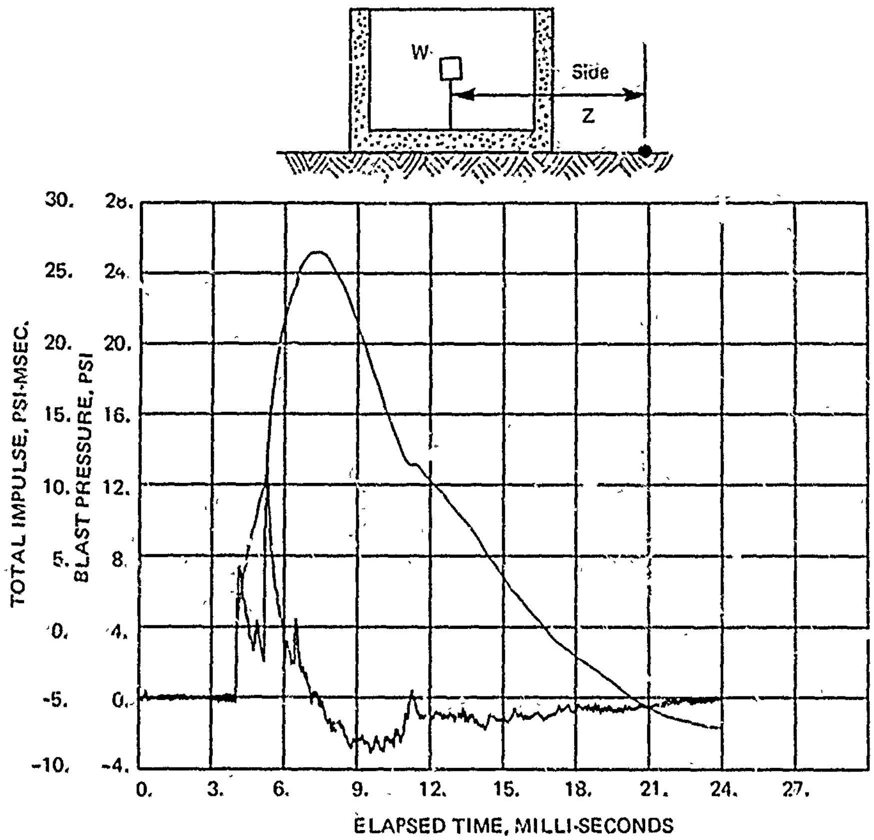


Figure A-20. Blast environm



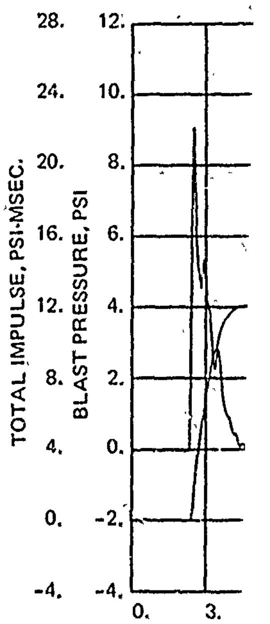
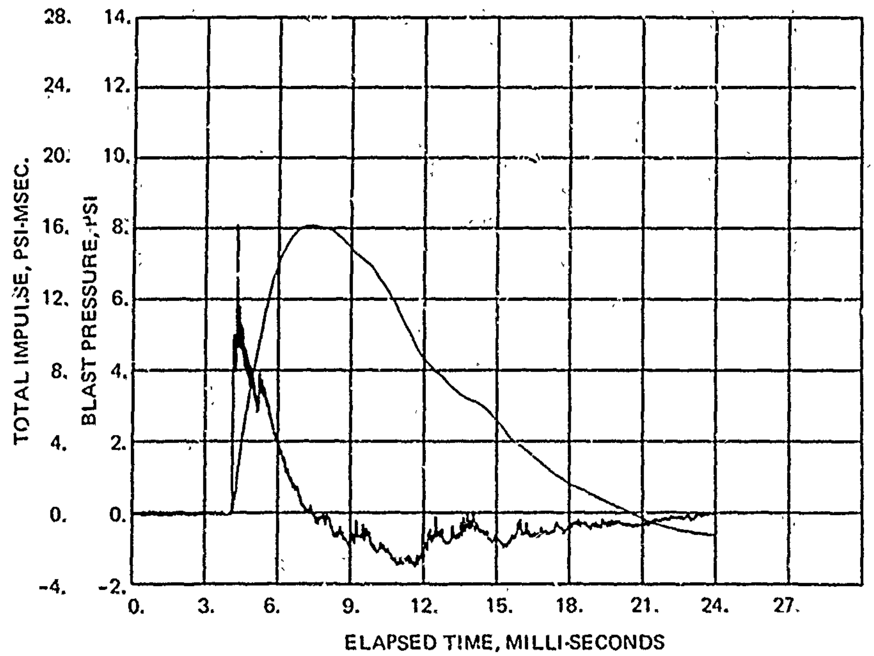


Figure A-19. Blast environment outside large 3-wall cubicle without roof: explosive charges of 1.5 pounds; Z = 6.99 ft/lb$^{1/3}$.



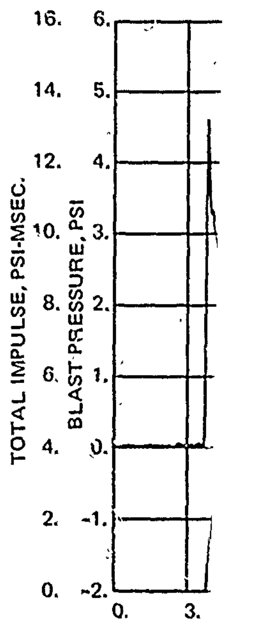
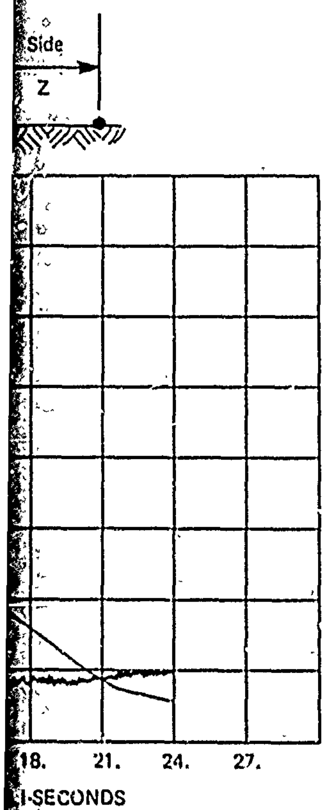
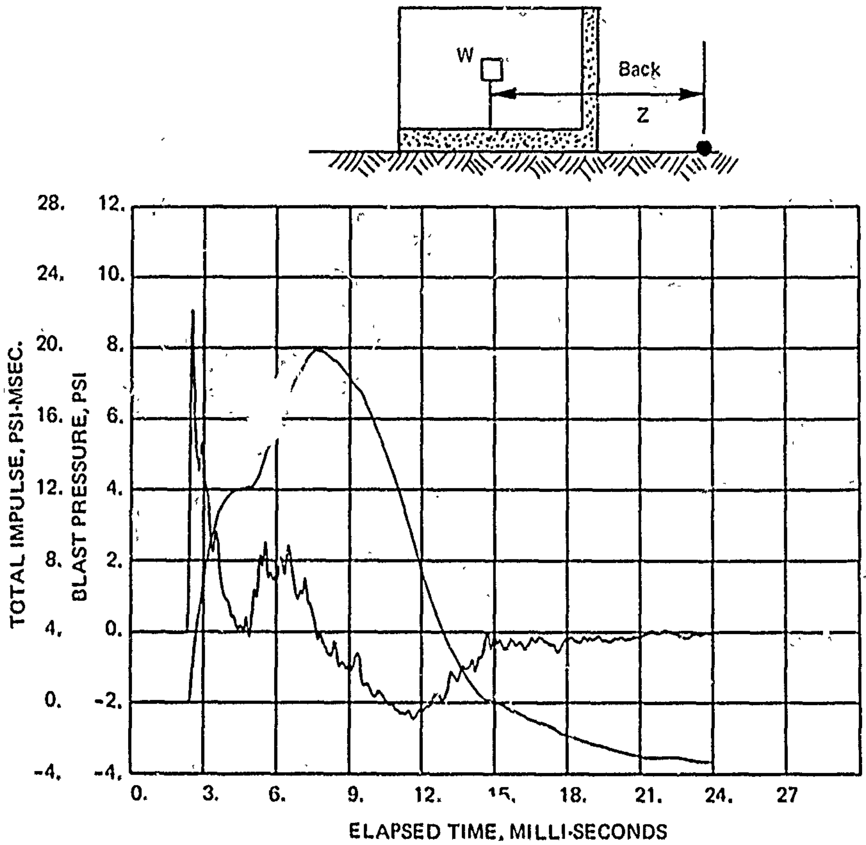
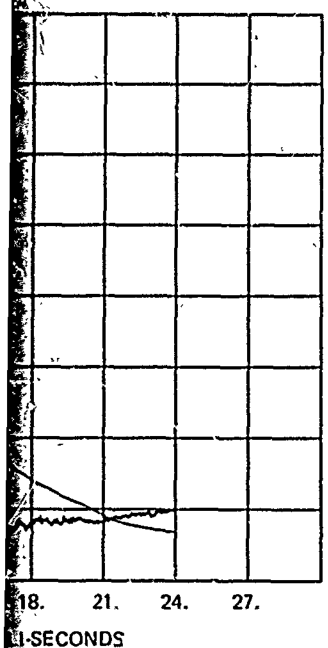


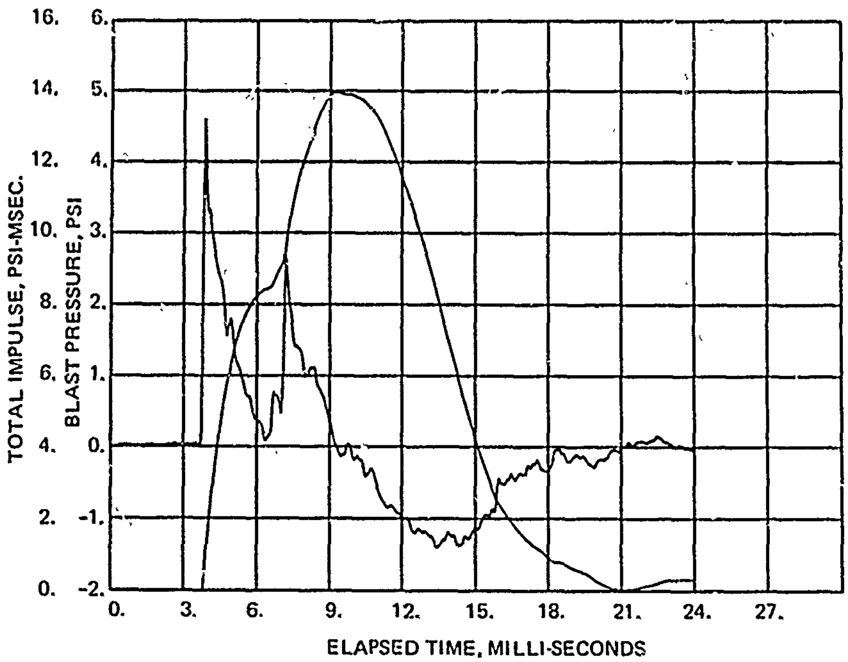
Figure A-20. Blast environment outside large 3-wall cubicle without roof: explosive charges of 1.5 pounds; Z = 14.0 ft/lb$^{1/3}$.





explosive charges of 1.5 pounds; $Z = 6.99$ ft/lb$^{1/3}$.





explosive charges of 1.5 pounds; $Z = 14.0$ ft/lb$^{1/3}$.

3

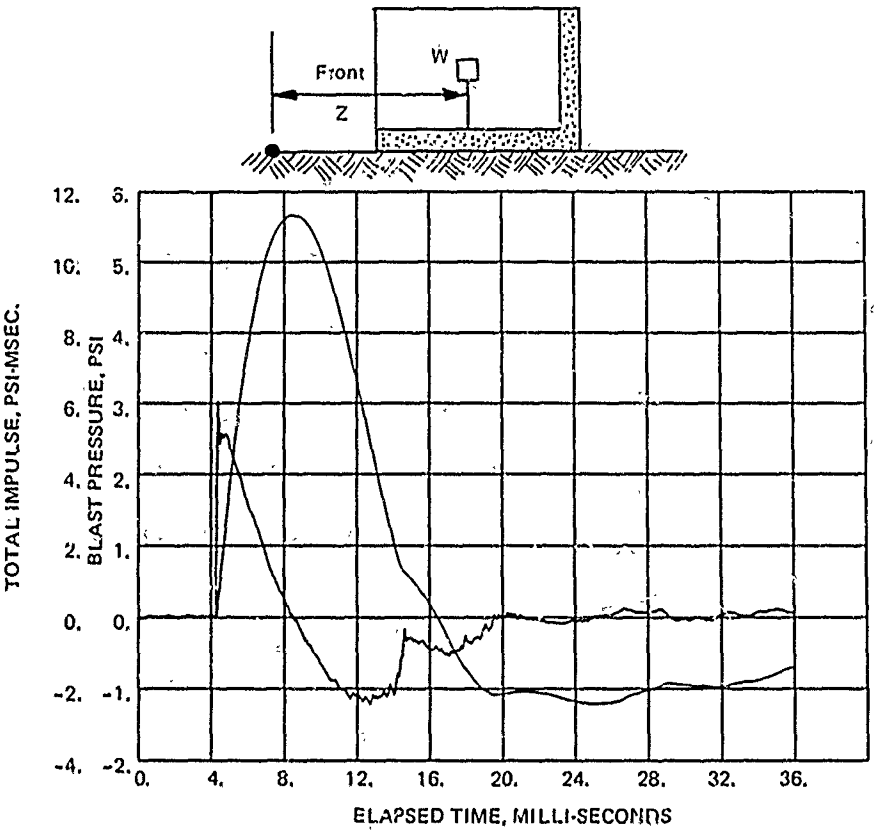


Figure A-21. Blast

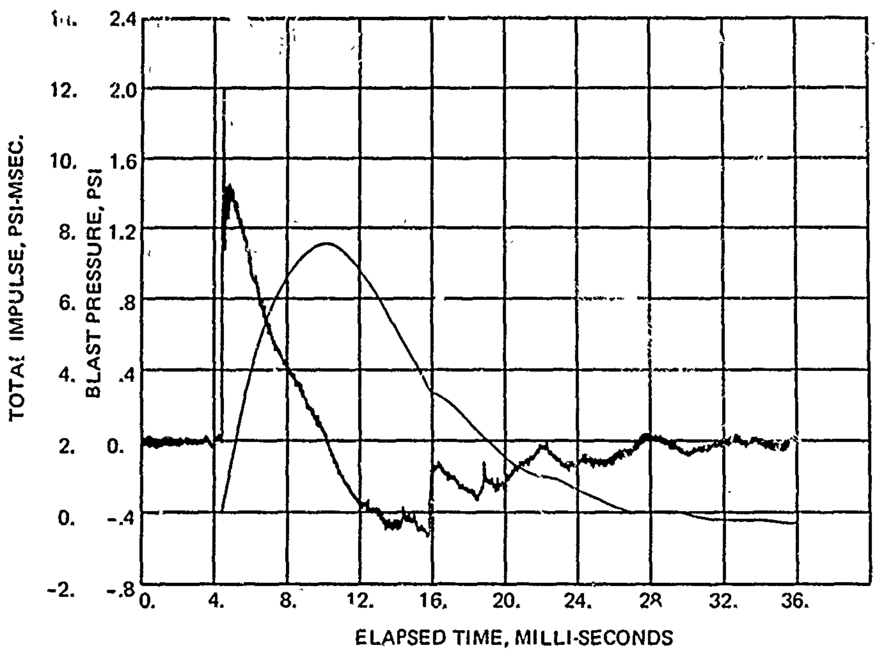


Figure A-22. Blast en

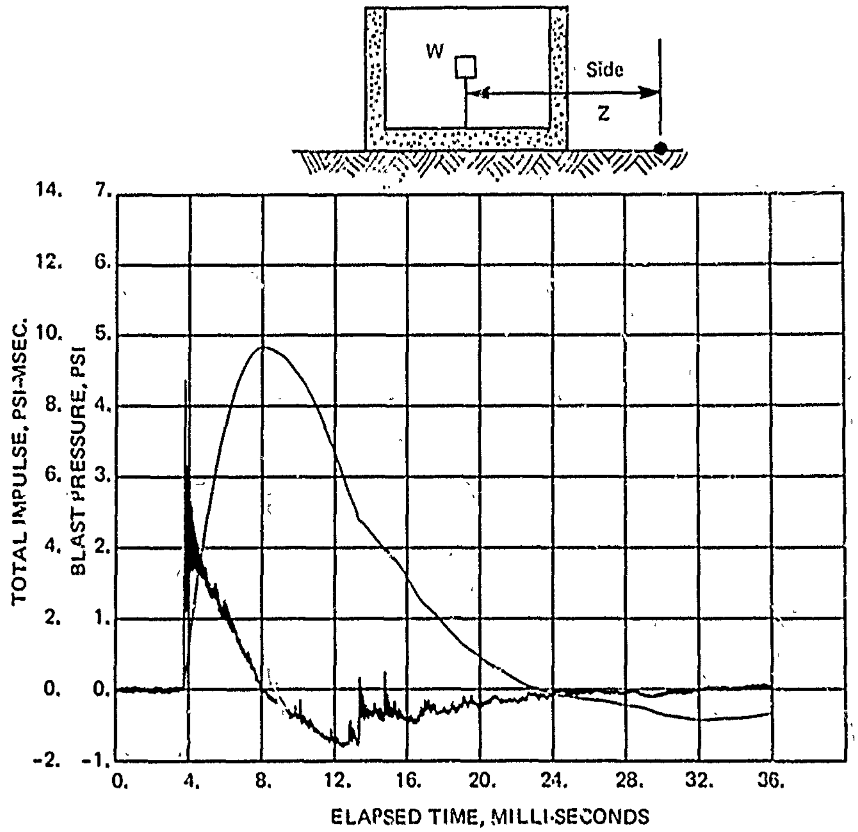


Figure A-21. Blast environment outside large 3 wall cubicle without roof. explosive charges of 1.5 pounds, Z = 28.0 ft/lb$^{1/3}$.

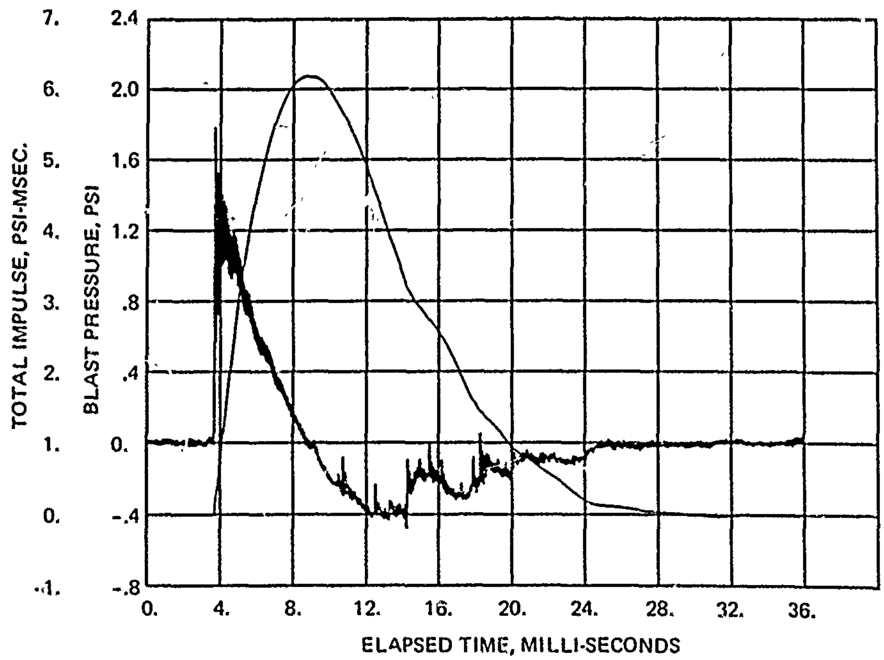
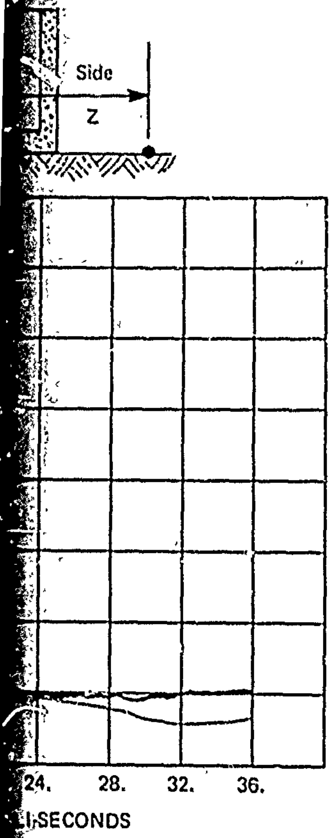
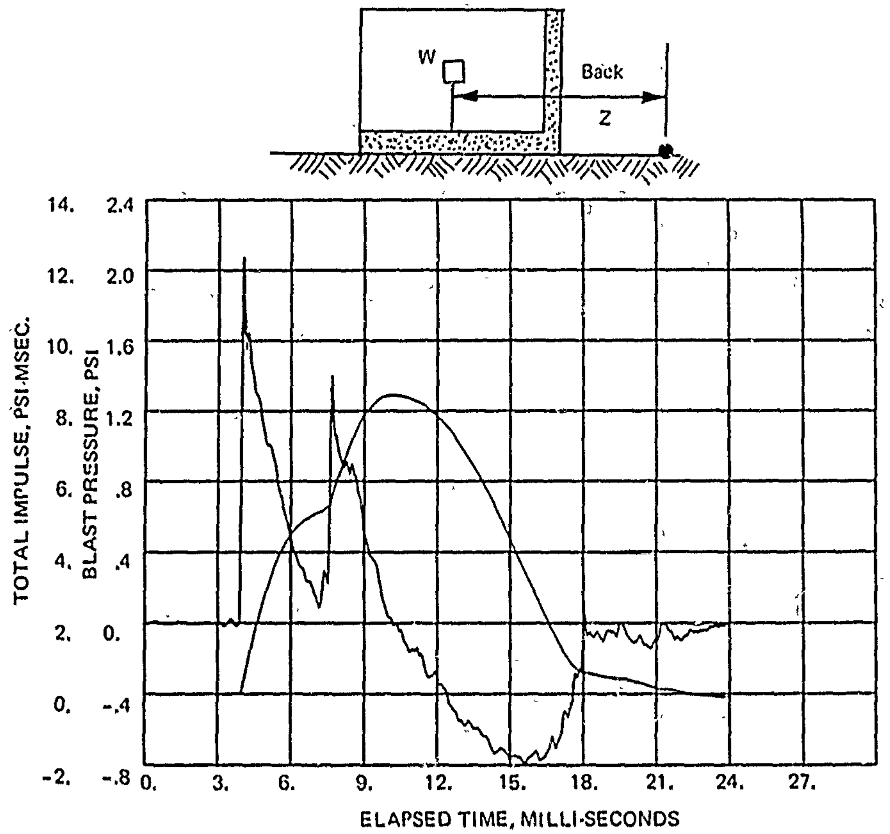
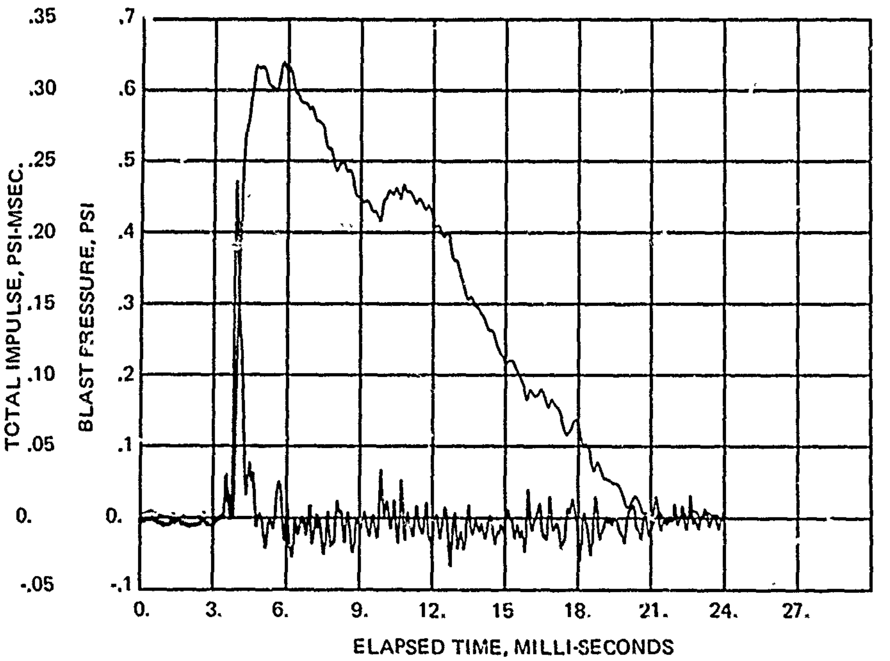


Figure A-22. Blast environment outside large 3-wall cubicle without roof. explosive charges of 1.5 pounds, Z = 43.7 ft/lb$^{1/3}$



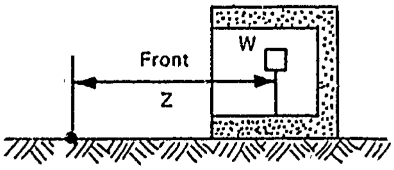


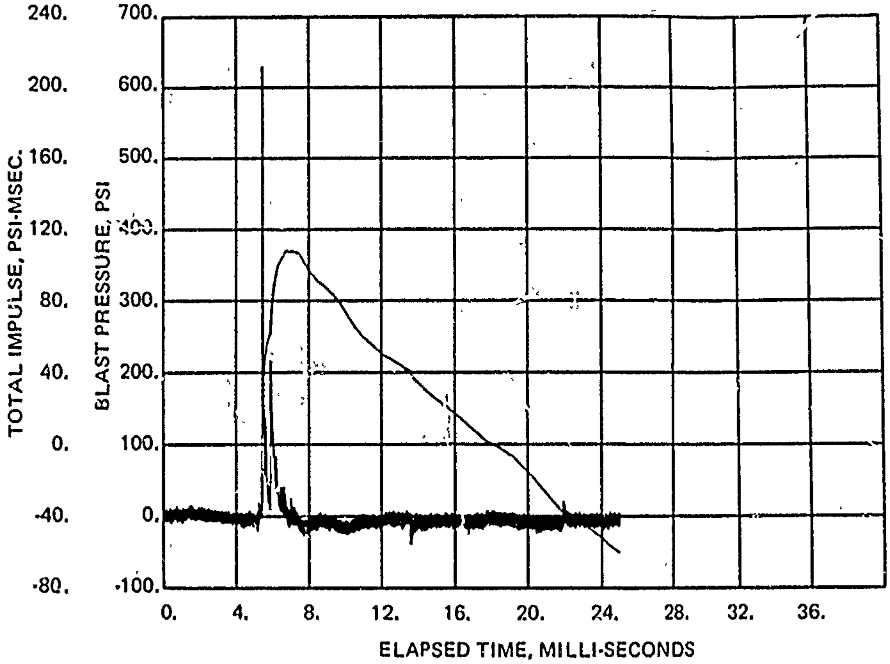
of: explosive charges of 1.5 pounds; $Z \approx 28.0$ ft/lb$^{1/3}$.



of: explosive charges of 1.5 pounds; $Z = 43.7$ ft/lb$^{1/3}$

3





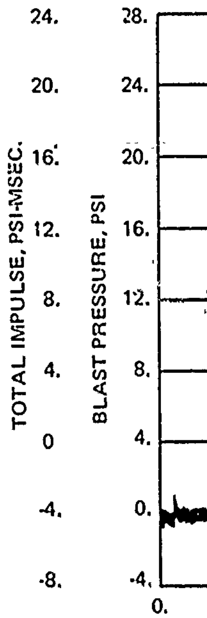
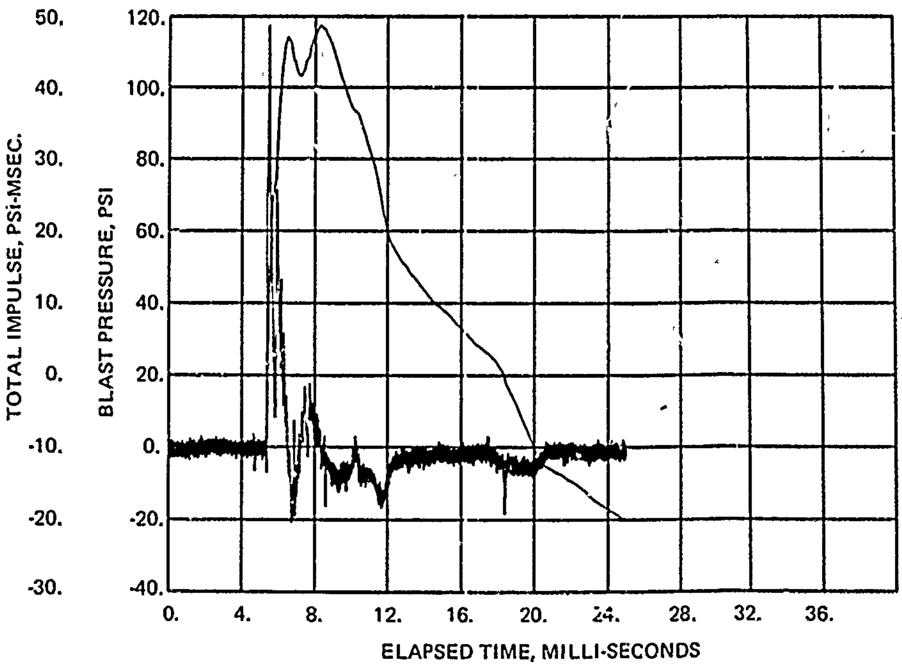


Figure A-23. Blast environment



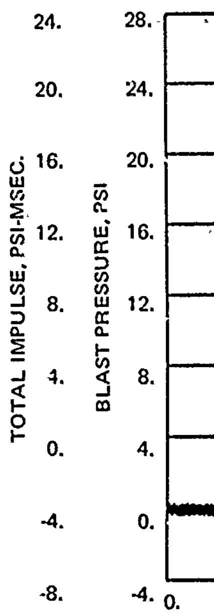
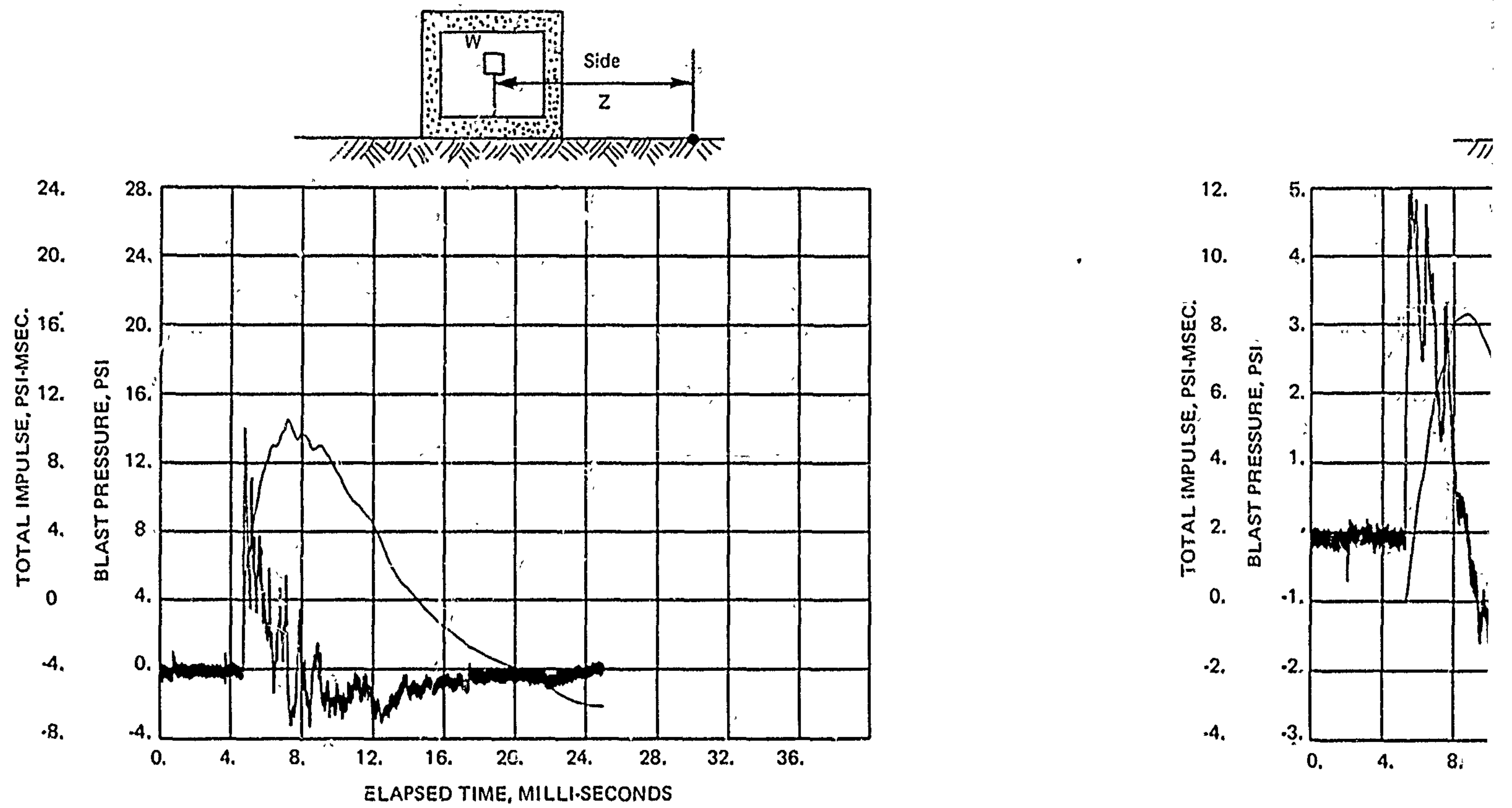
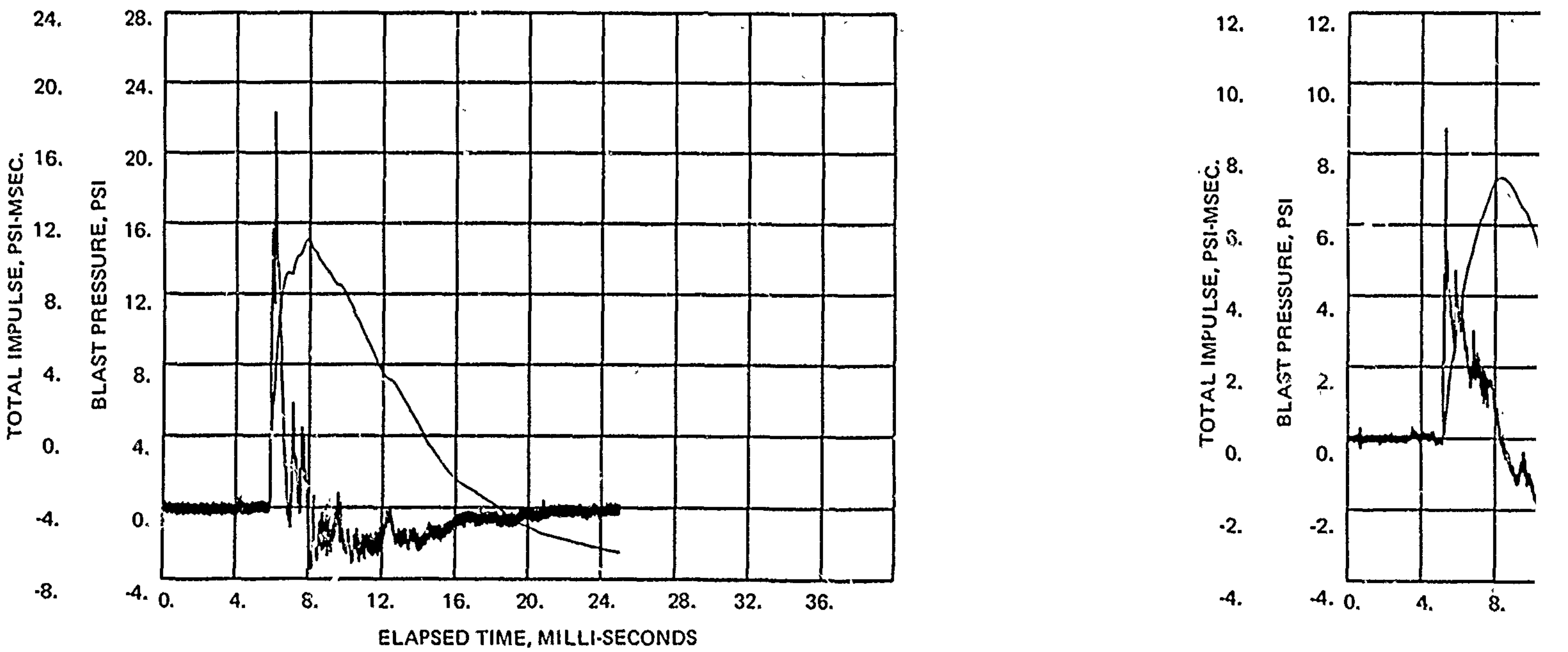


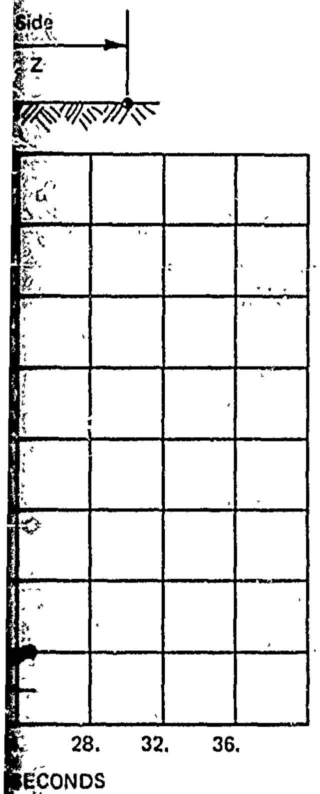
Figure A-24. Blast environmen

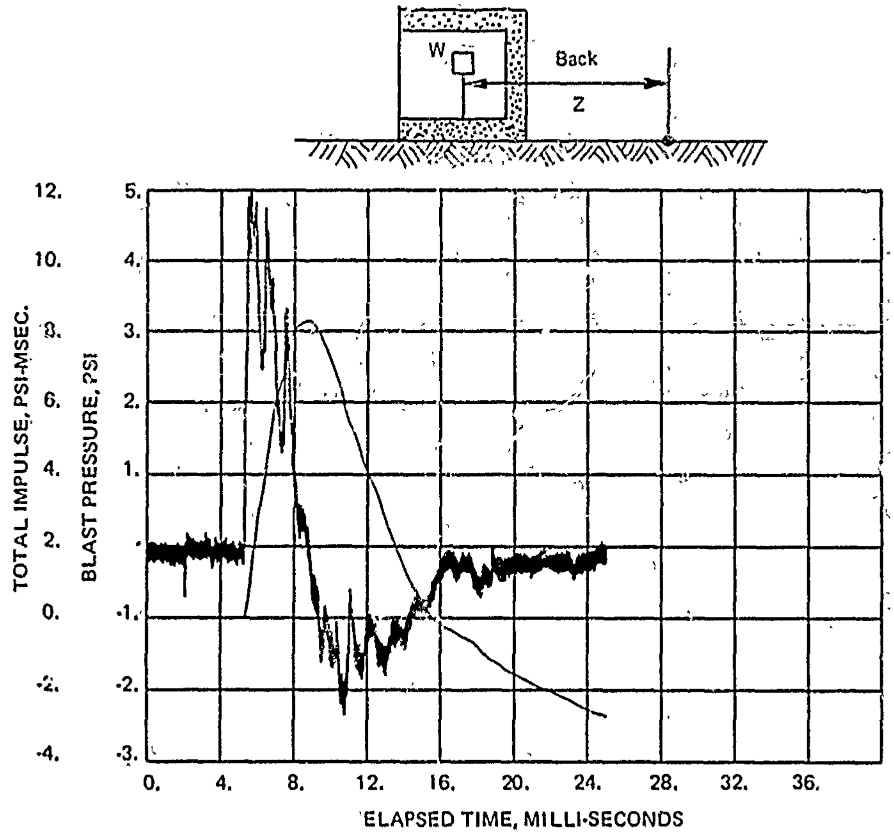


re A-23. Blast environment outside small 3-wall cubicle with roof. explosive charges of 1.0 pound; Z = 2.0 ft/lb$^{1/3}$.

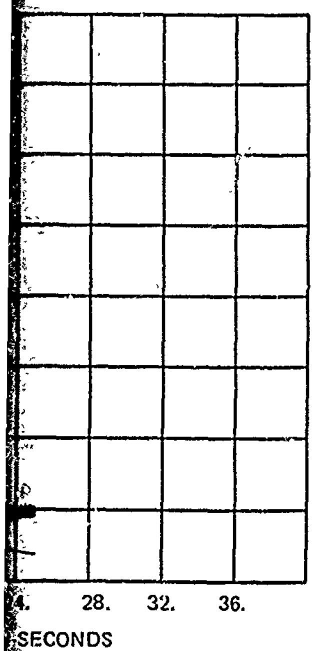


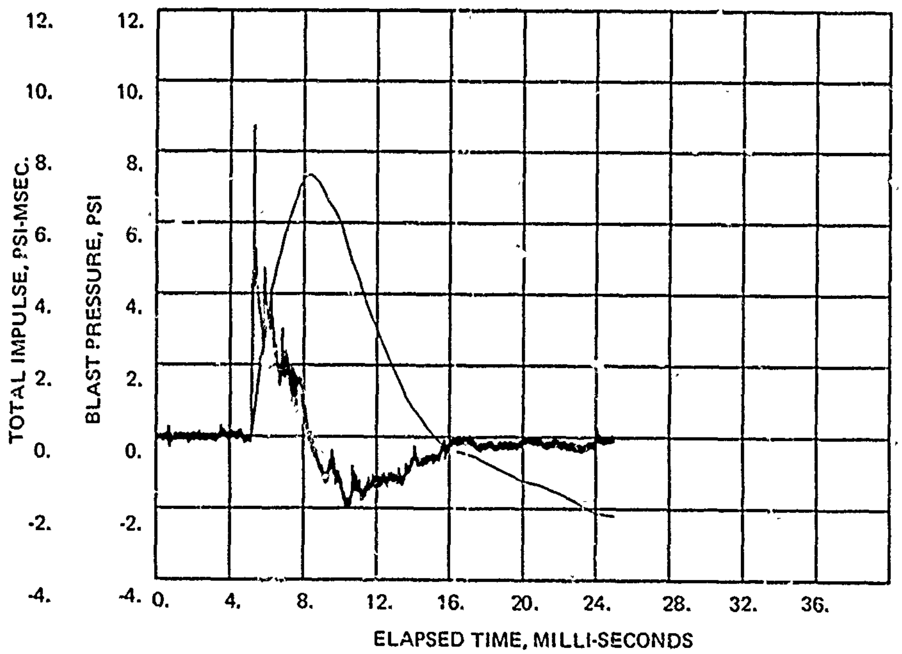
ure A-24. Blast environment outside small 3-wall cubicle with roof. explosive charges of 1.0 pound, Z = 4.0 ft/lb$^{1/3}$.





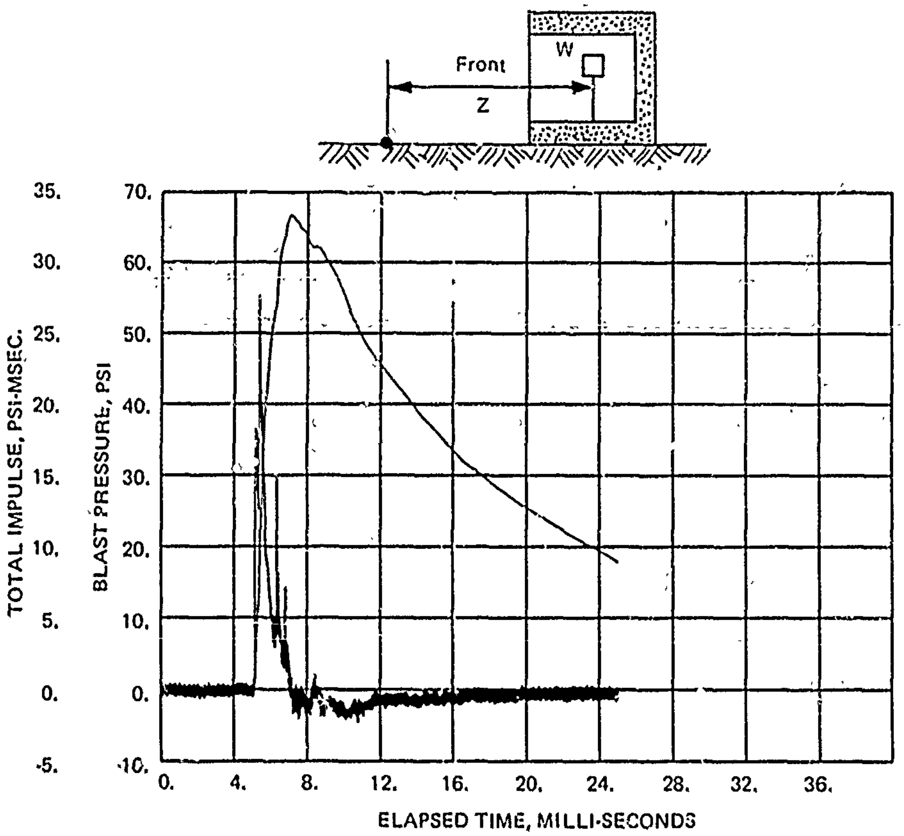
explosive charges of 1.0 pound; $Z = 2.0$ ft/lb$^{1/3}$.





explosive charges of 1.0 pound; $Z = 4.0$ ft/lb$^{1/3}$.

3



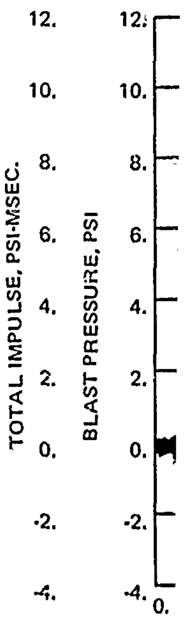
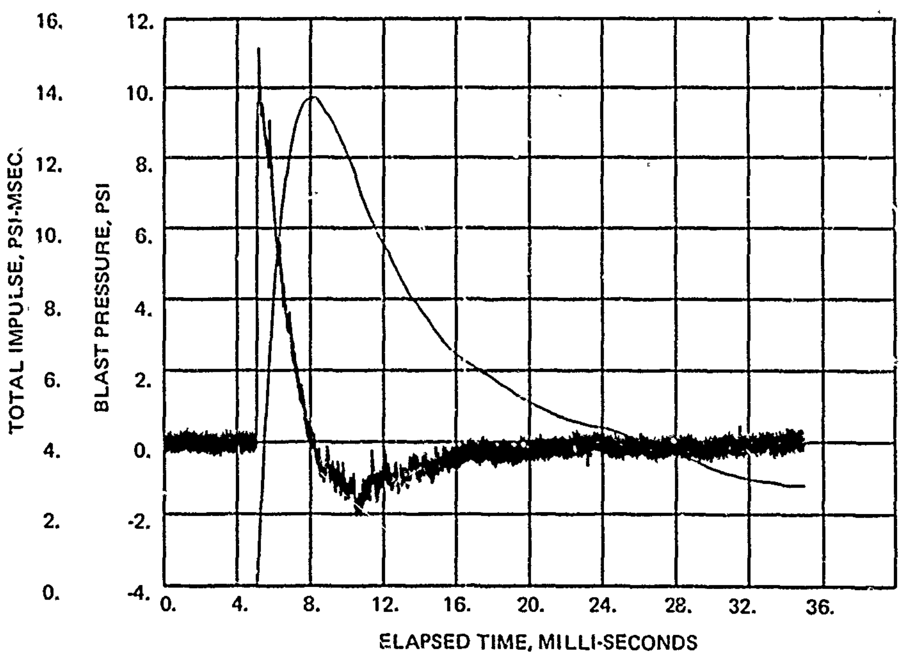


Figure A-25. Blast environmei



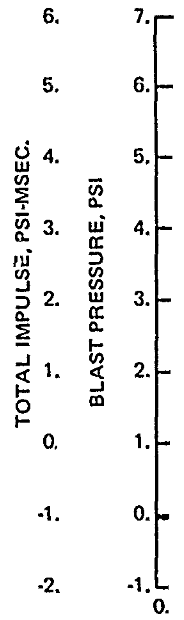
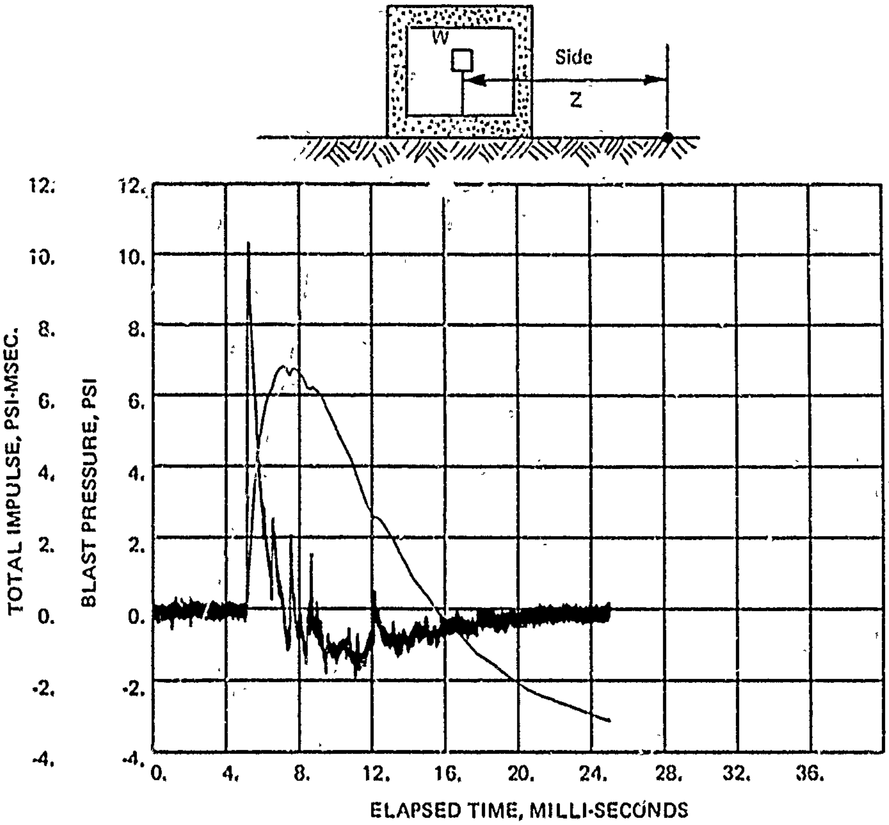


Figure A-26. Blast envaonmc



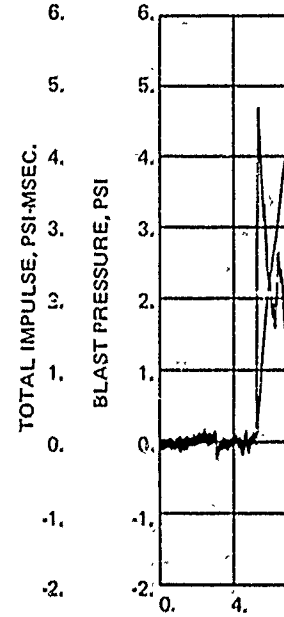
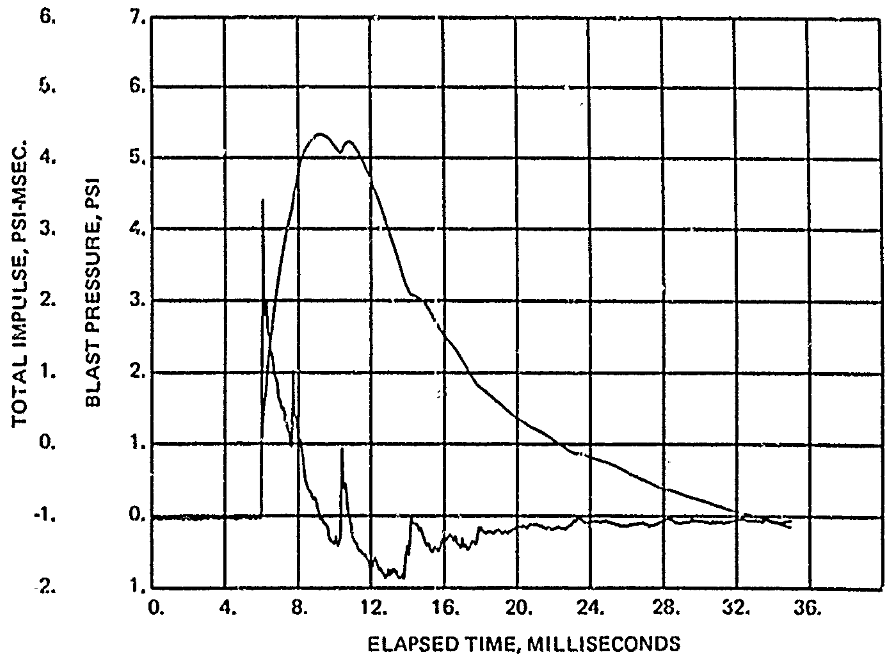


Figure A 25. Blast environment outside small 3 wall cubicle with roof. explosive charges of 1.0 pound, Z = 8.0 ft/lb$^{1/3}$.



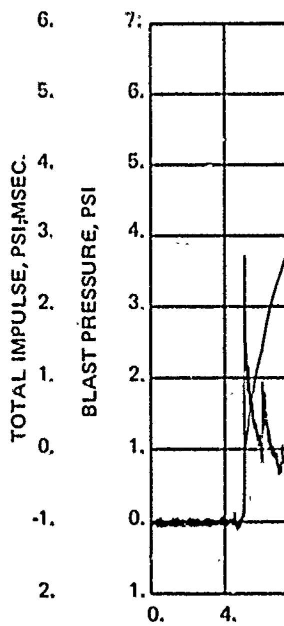
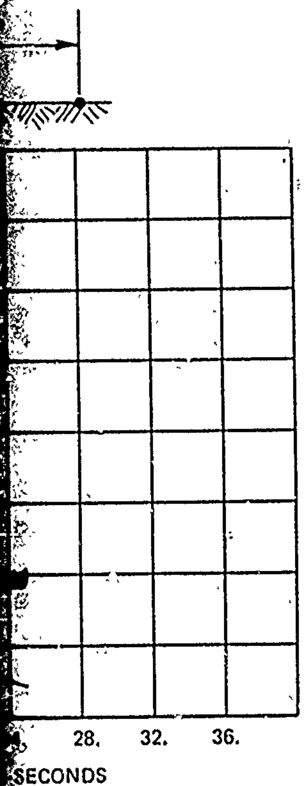
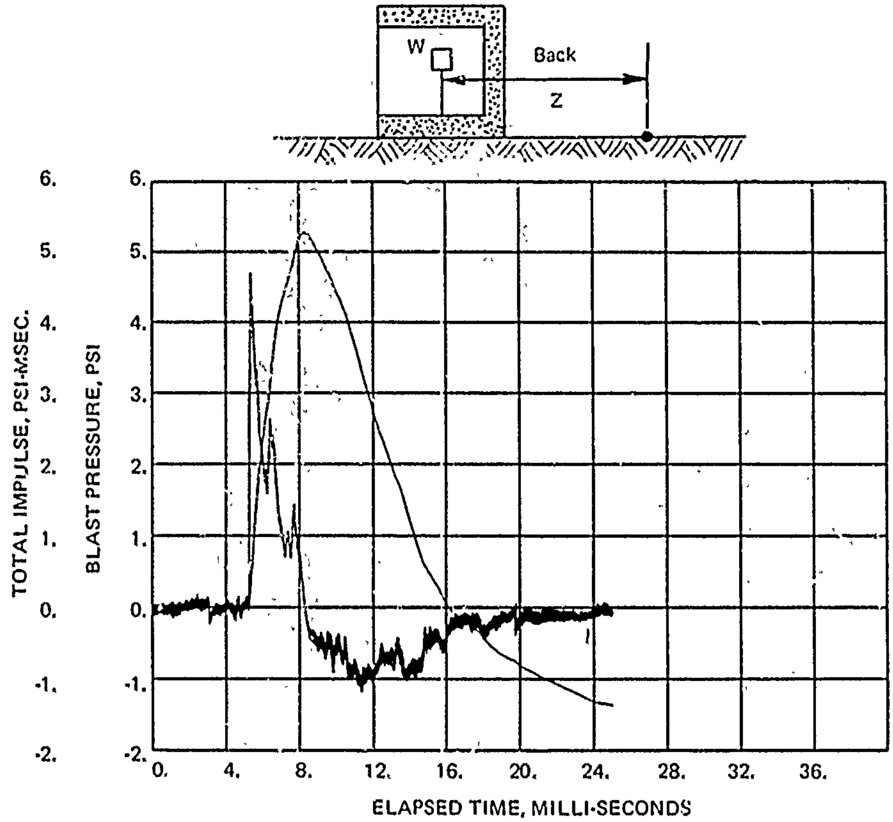


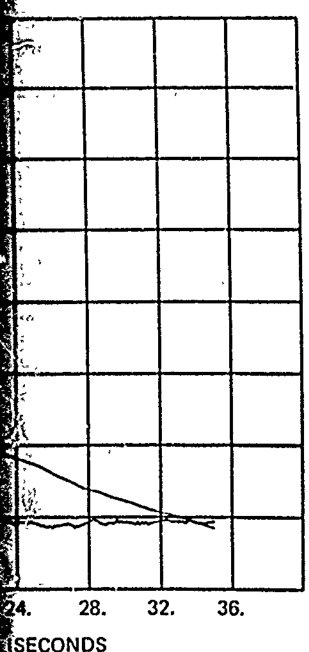
Figure A 26. Blast environment outside small 3 wall cubicle with roof. explosive charges of 1.0 pound, Z = 16.0 ft/lb$^{1/3}$.

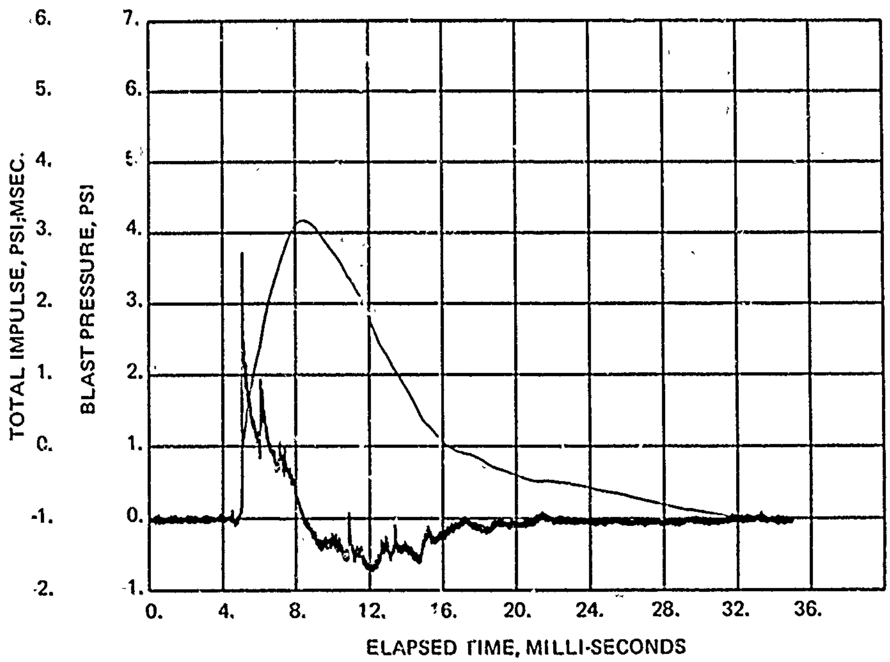
2





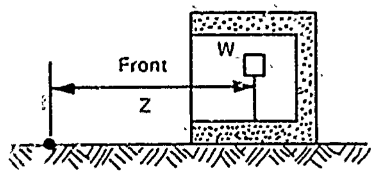
xplosive charges of 1.0 pound; $Z = 8.0$ ft/lb$^{1/3}$.

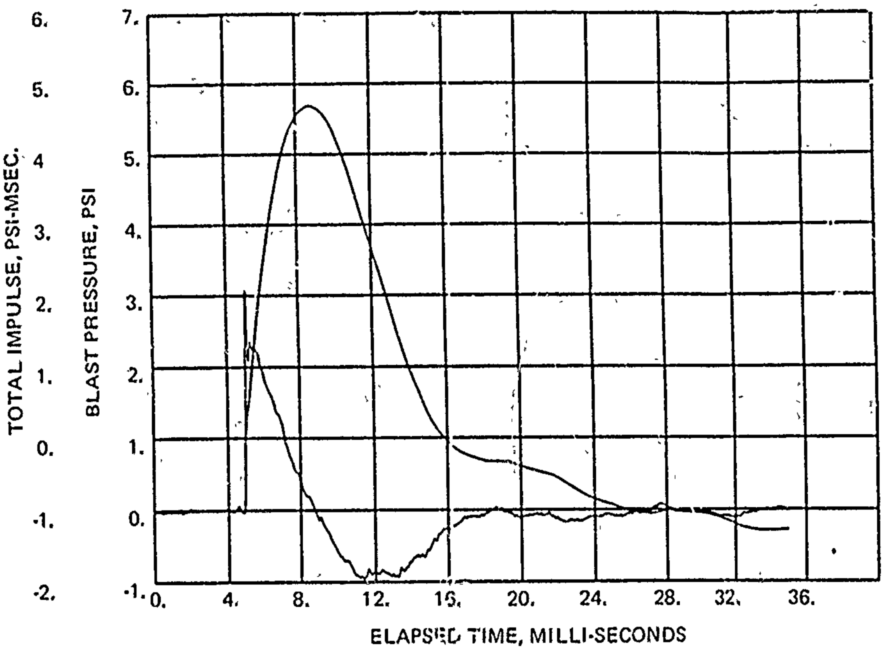


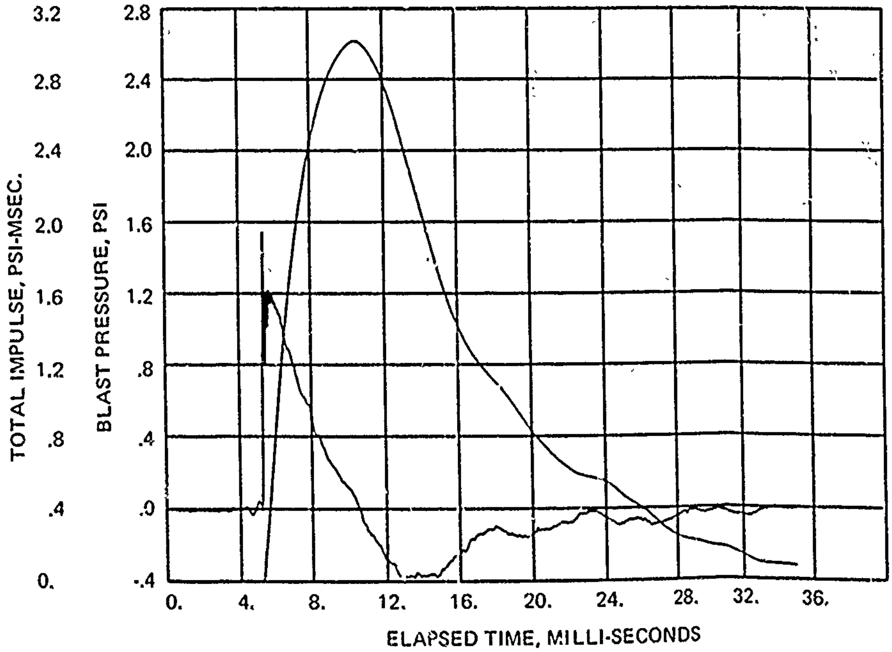


explosive charges of 1.0 pound; $Z = 16.0$ ft/lb$^{1/3}$.

3







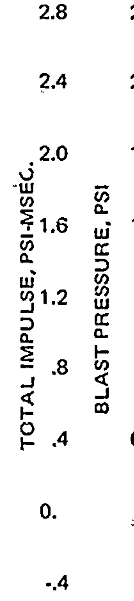


Figure A-27 Blast e

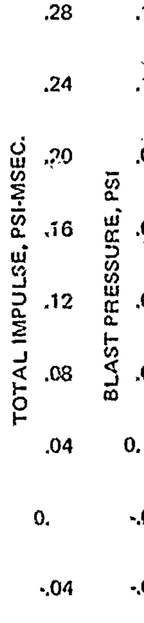
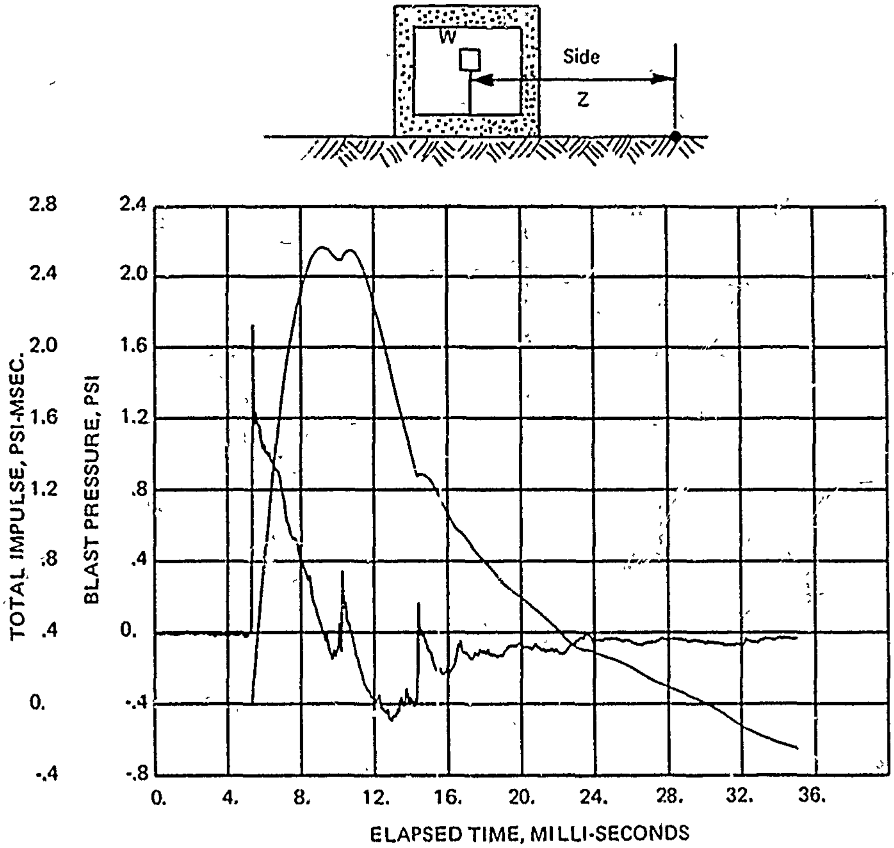


Figure A-28. Blast er



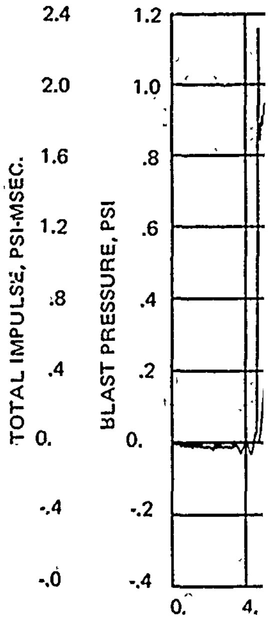
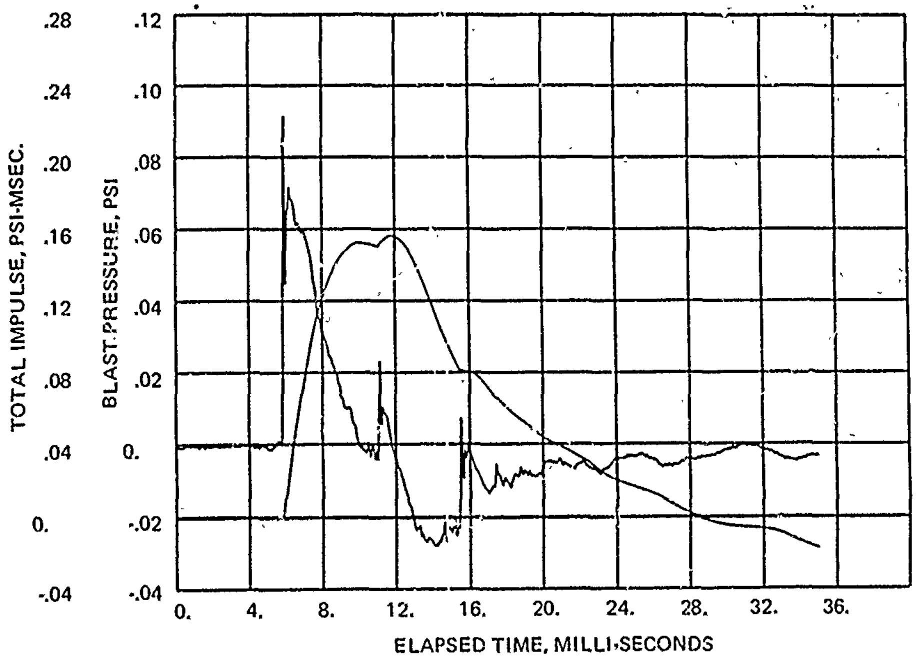


Figure A-27. Blast environment outside small 3 wall cubicle with roof. explosive charges of 1.0 pound, Z = 32 ft/lb$^{1/3}$.



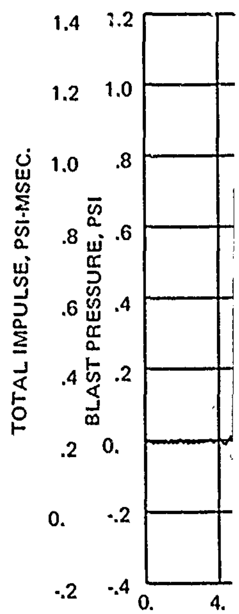
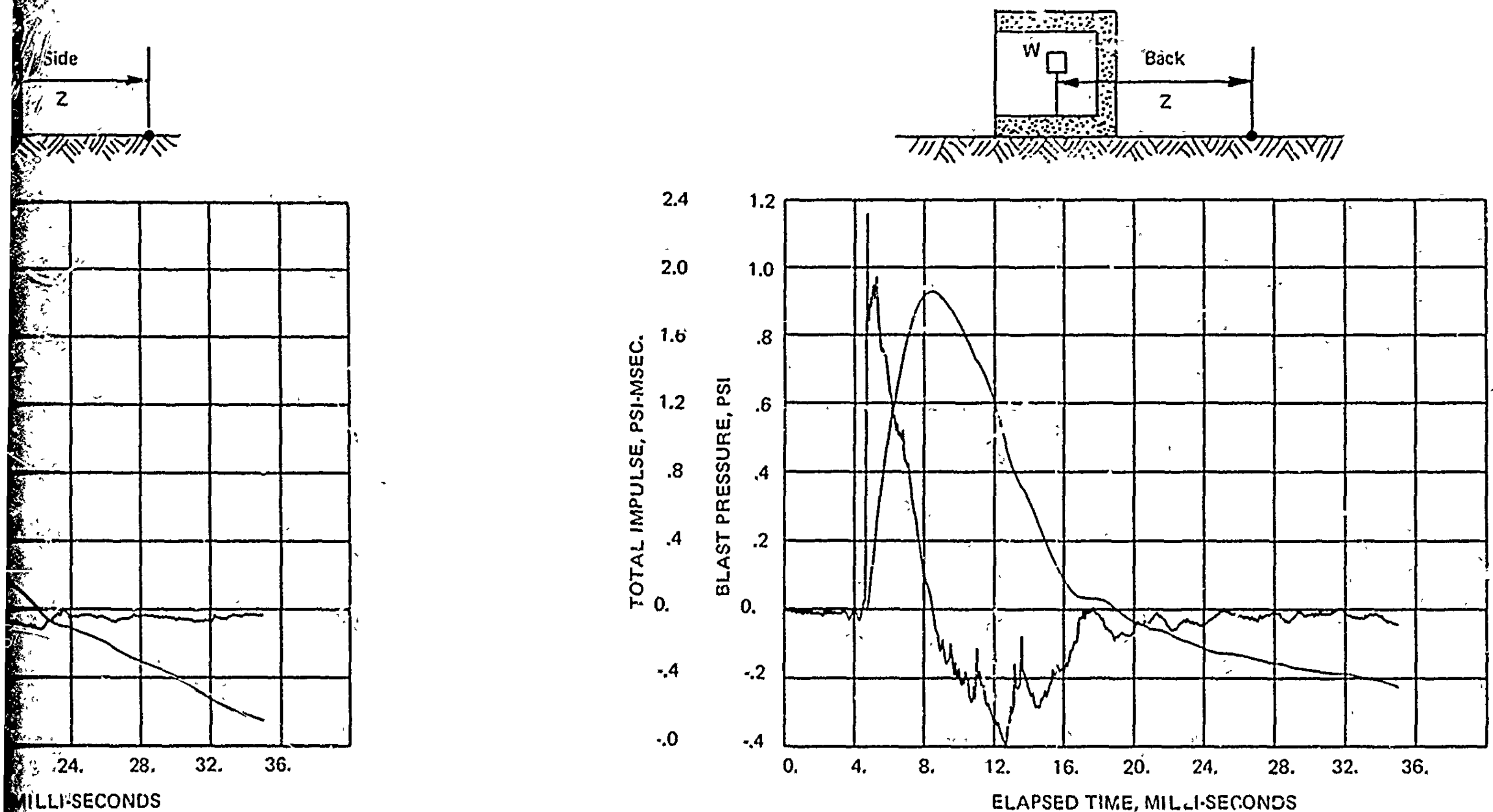
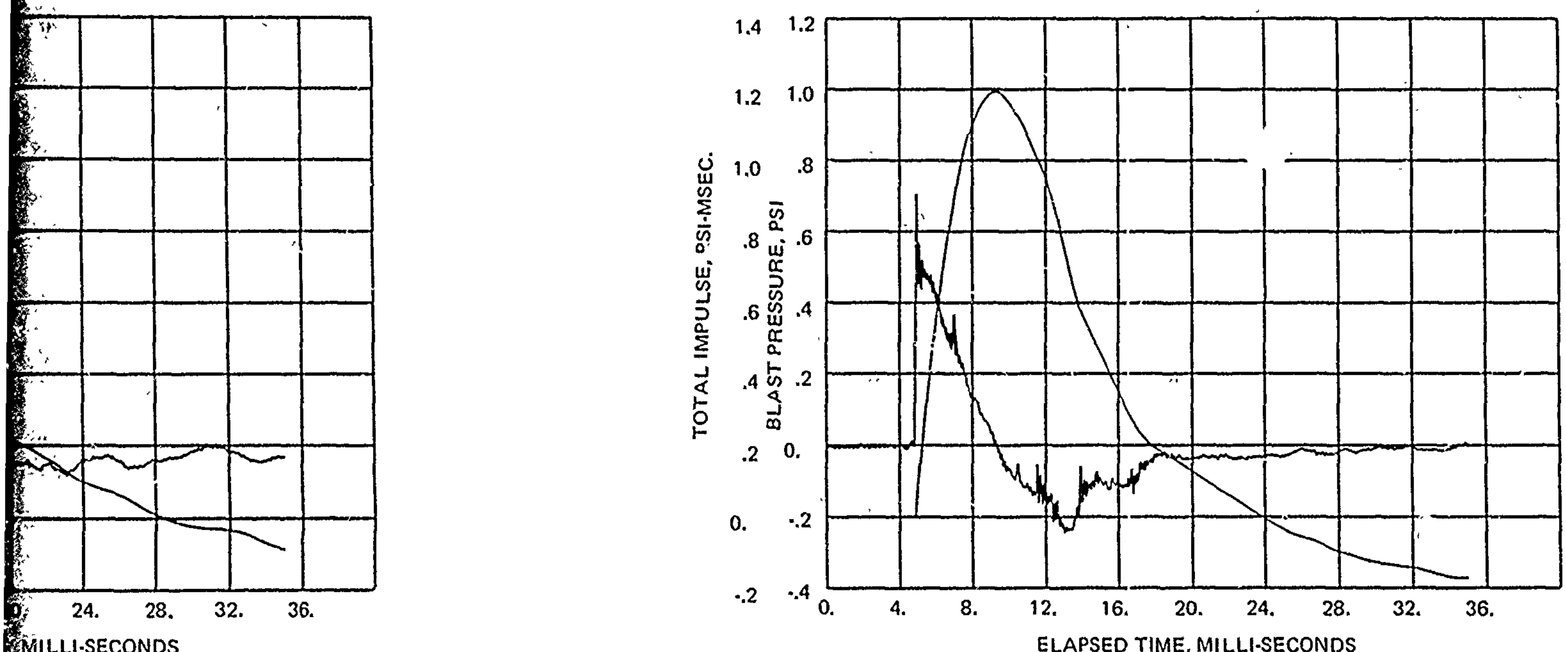


Figure A-28. Blast environment outside small 3-wall cubicle with roof. explosive charges of 1.0 pound, Z = 50 ft/lb$^{1/3}$.

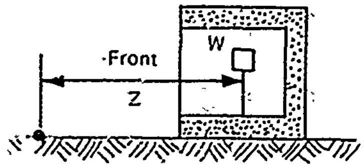


with roof: explosive charges of 1.0 pound; $Z = 32$ ft/lb$^{1/3}$.



with roof: explosive charges of 1.0 pound; $Z = 50$ ft/lb$^{1/3}$.

3



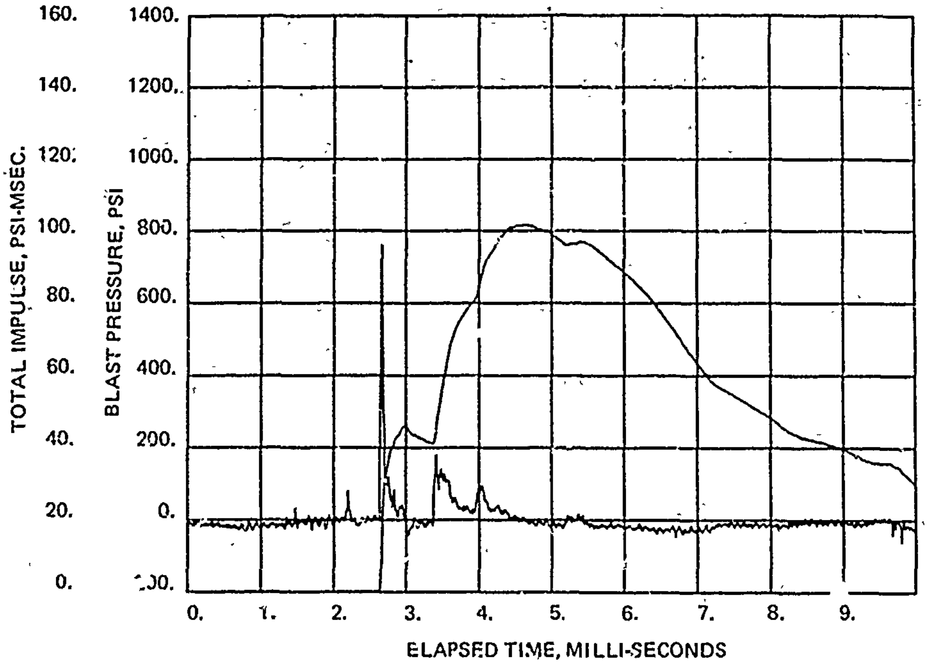
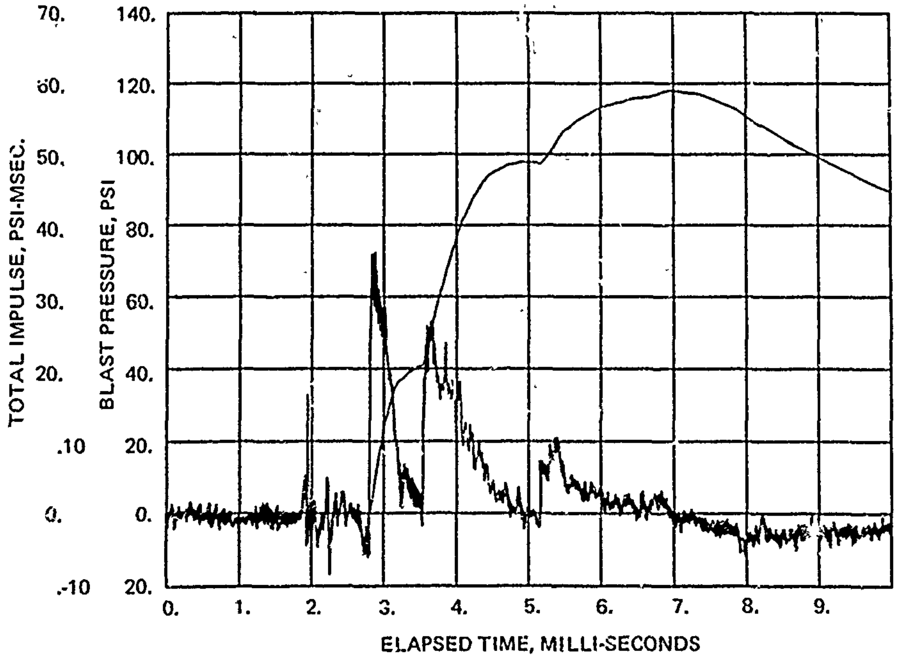


Figure A-29. Bl



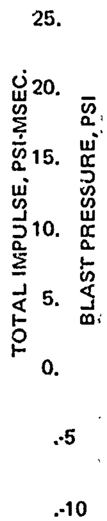


Figure A-30. Blast er

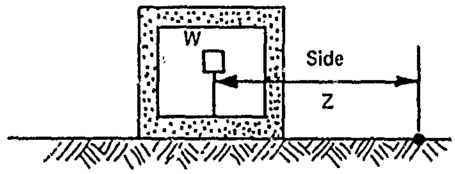
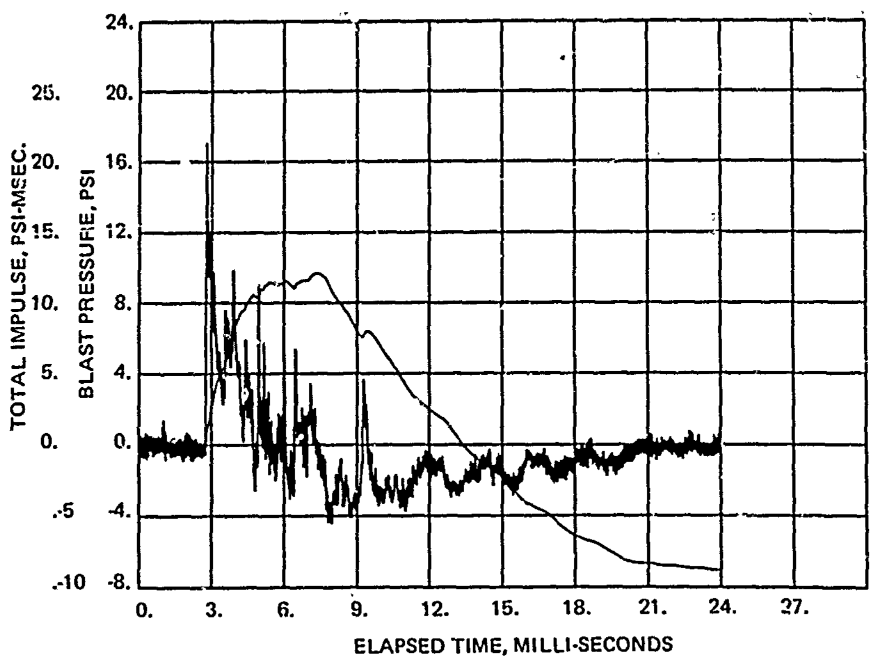


Figure A-29. Blast environment outside large 3-wall cubicle with roof: explosive charges of 1.5 pounds; $Z = 1.92\ ft/lb^{1/3}$.



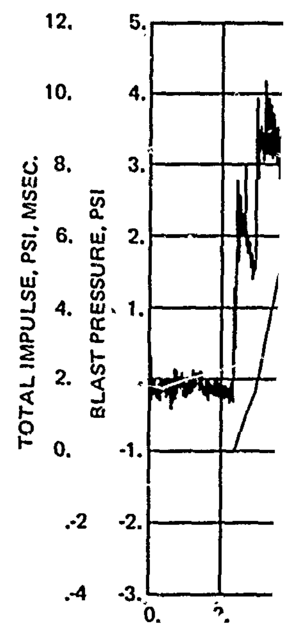
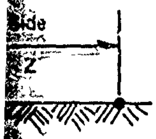
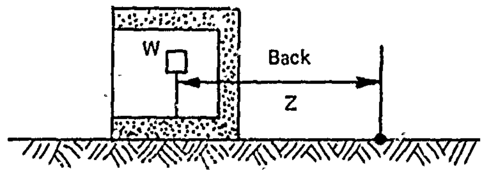
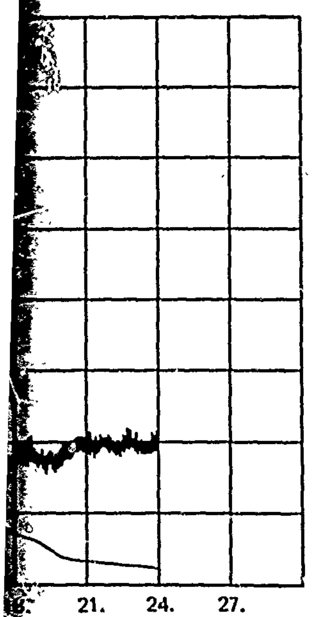


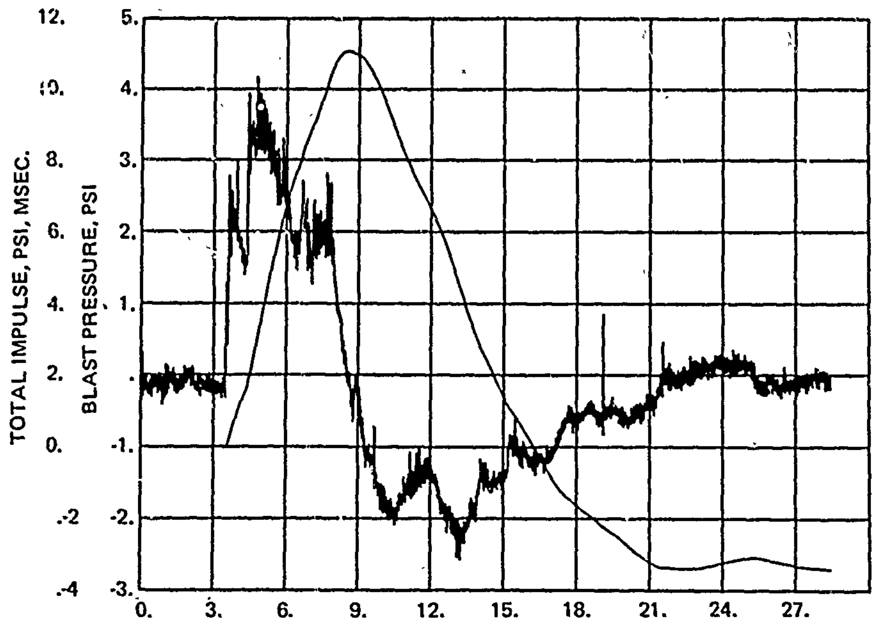
Figure A-30. Blast environment outside large 3-wall cubicle with roof: explosive charges of 1.5 pounds; $Z = 3.49\ ft/lb^{1/3}$.





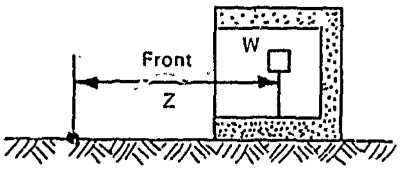
roof: explosive charges of 1.5 pounds; Z = 1.92 ft/lb$^{1/3}$.

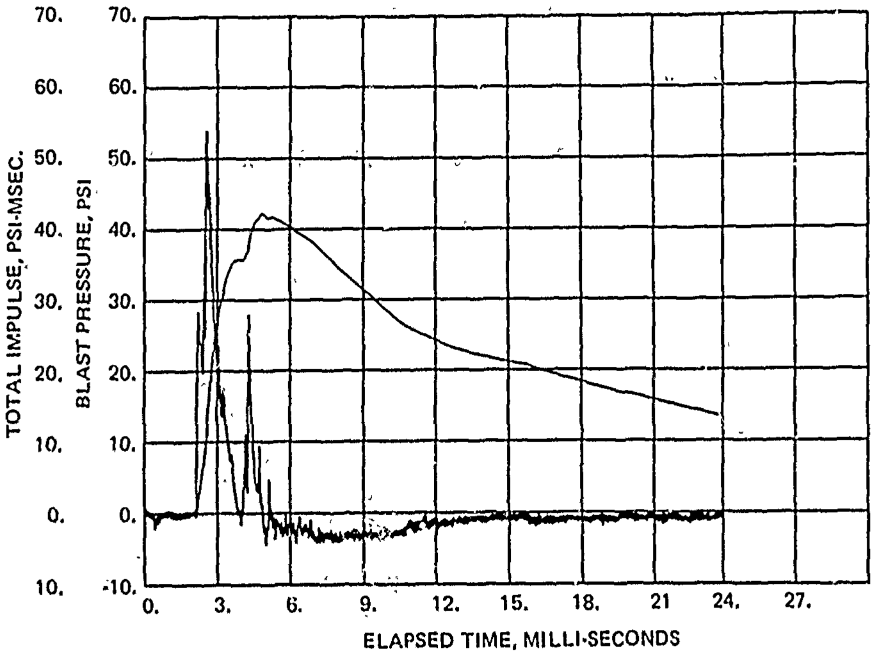




f: explosive charges of 1.5 pounds; Z = 3.49 ft/lb$^{1/3}$.

3





Figure

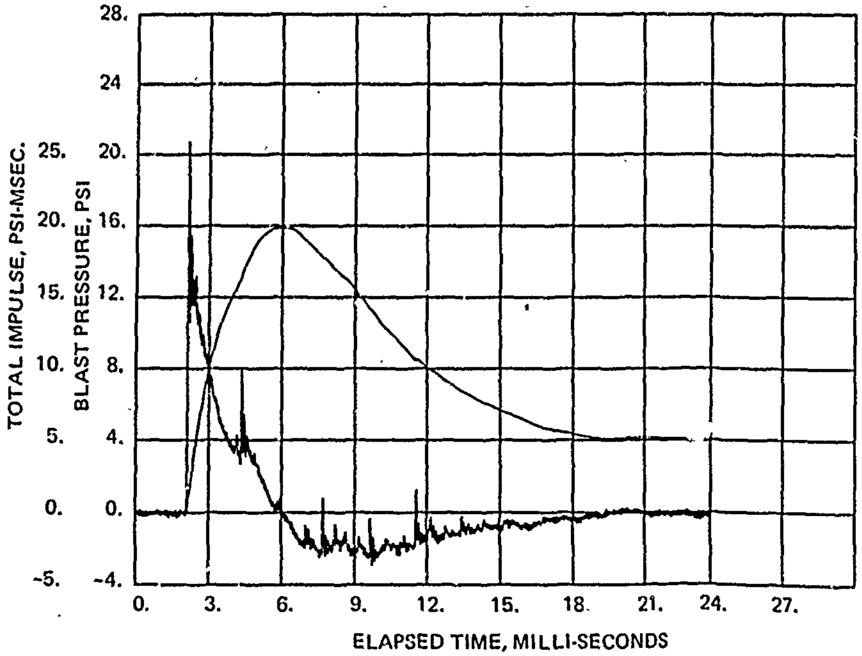
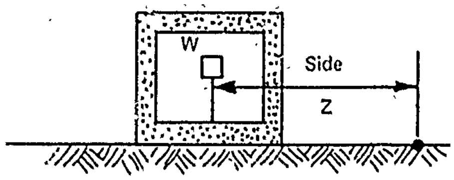


Figure A-3



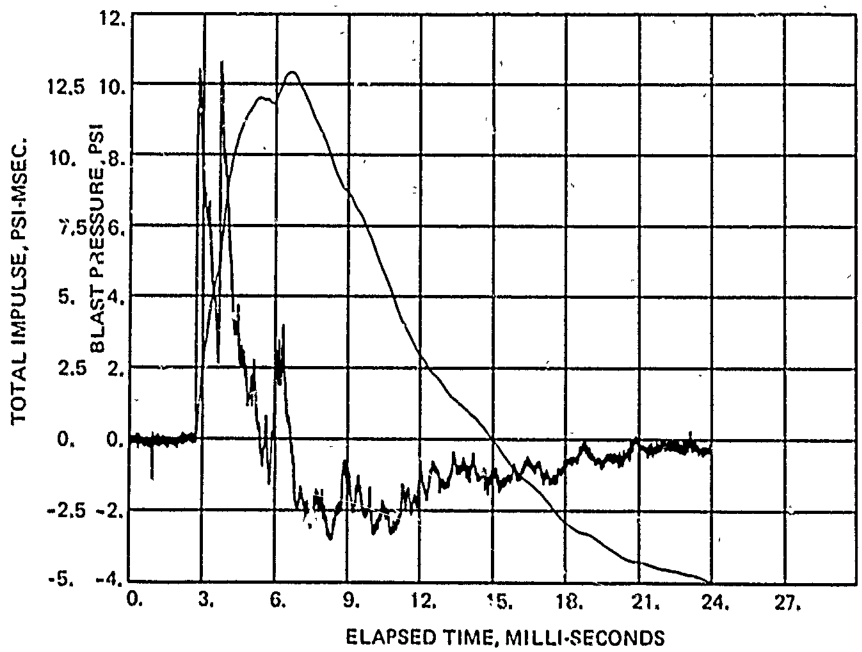


Figure A-31. Blast environment outside large 3-wall cubicle with roof. explosive charges of 1.5 pounds, Z = 6.99 ft/lb$^{1/3}$.

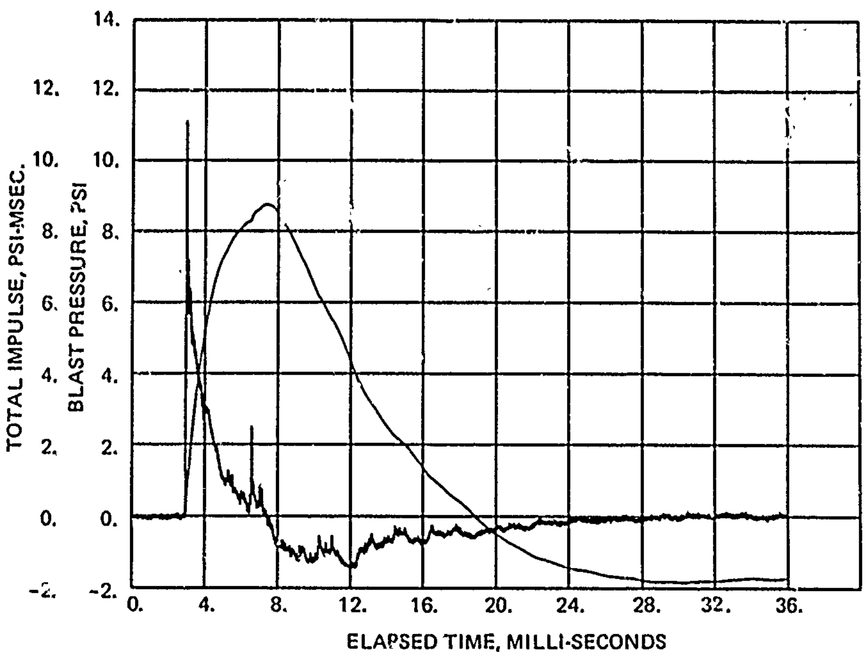
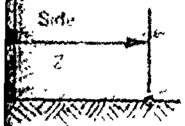
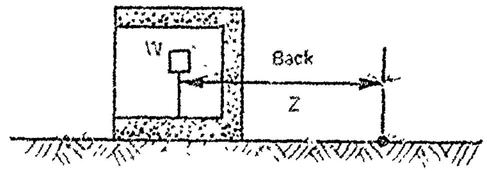
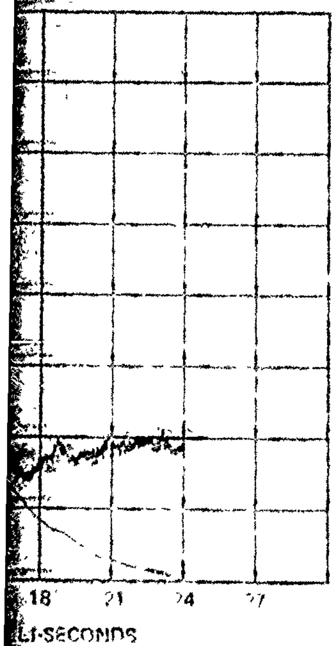
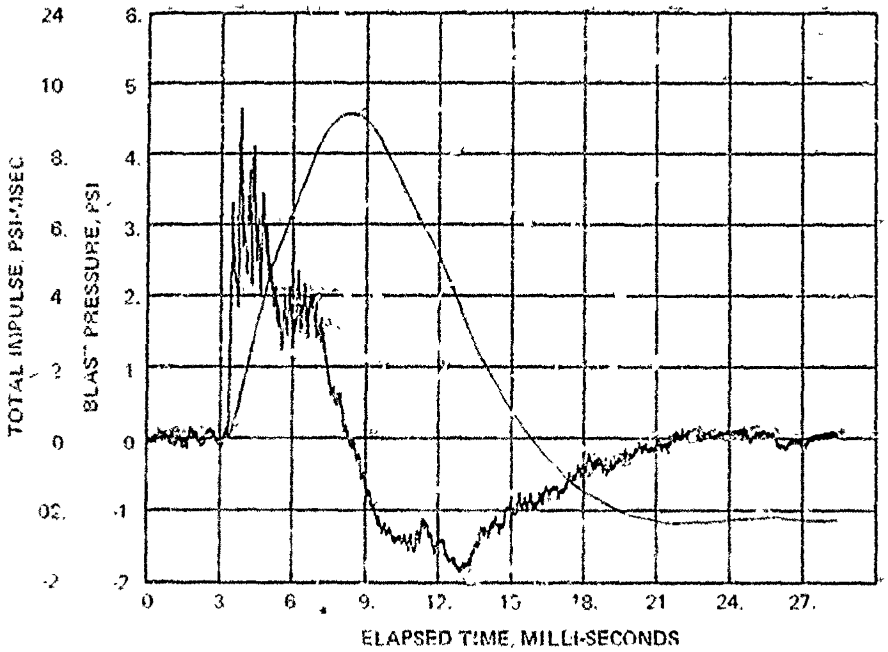


Figure A 32. Blast environment outside large 3 wall cubicle with roof. explosive charges of 1.5 pounds, Z = 14.0 ft/lb$^{1/3}$.

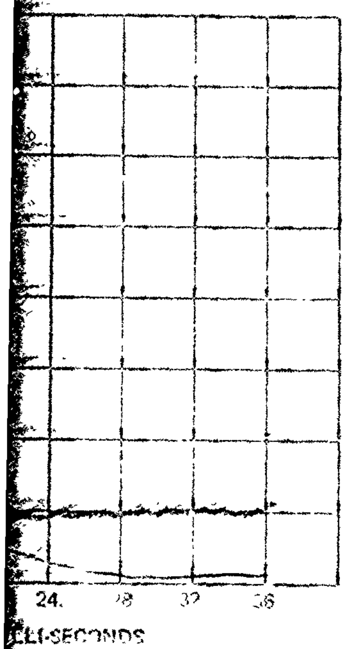


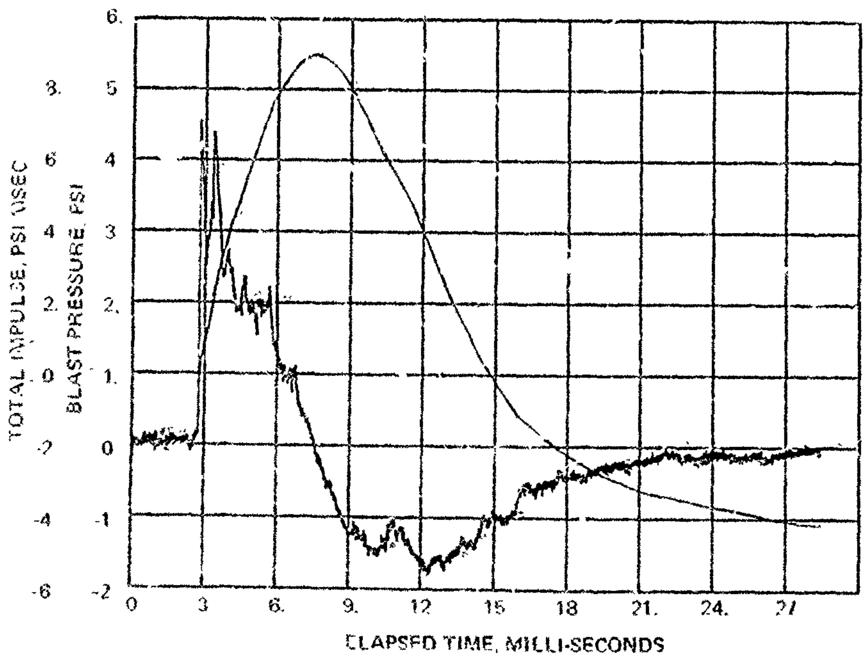




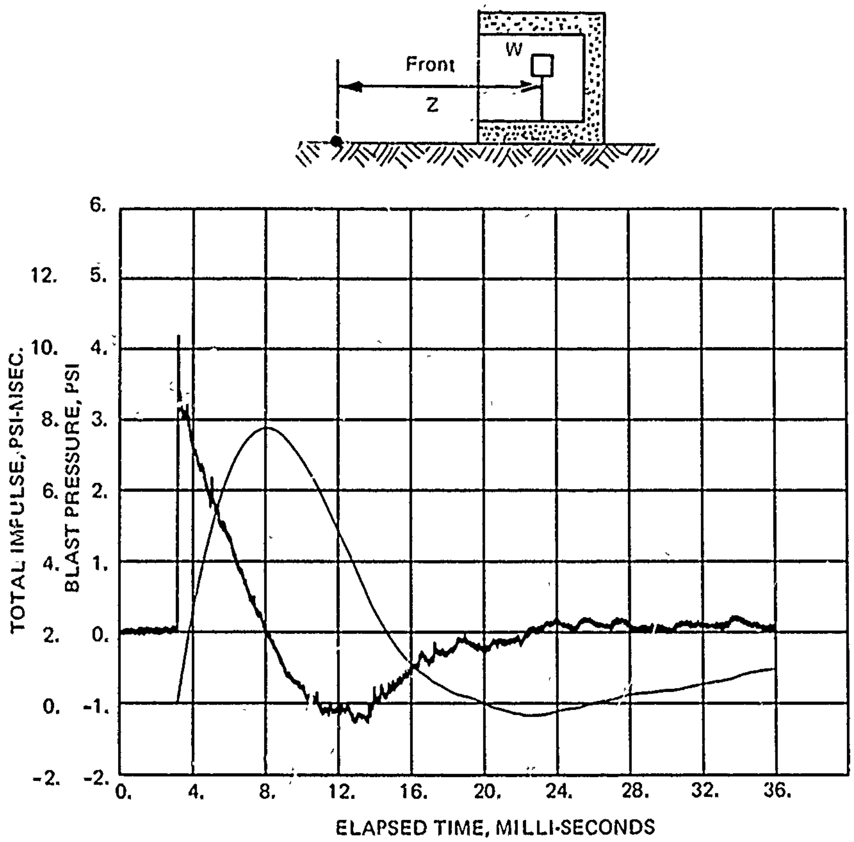


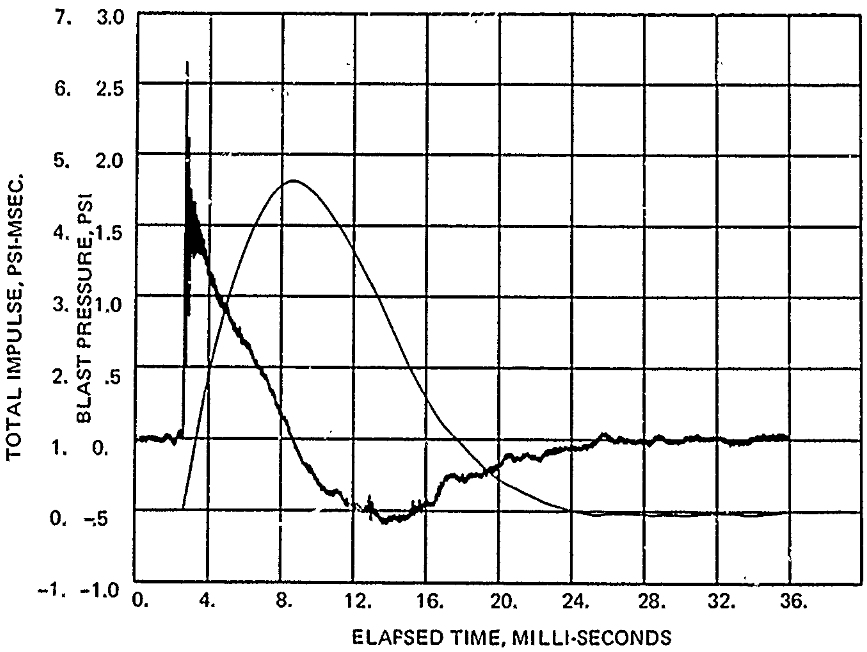
roof: explosive charges of 1.5 pounds; Z = 6.99 ft/lb$^{1/3}$.





f: explosive charges of 1.5 pounds, Z = 14.0 ft/lb$^{1/3}$





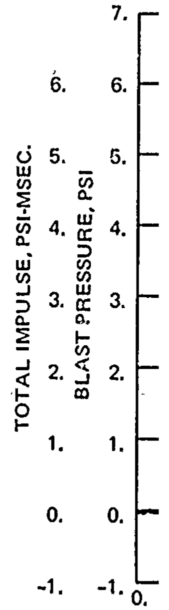


Figure A-33. Blast environ

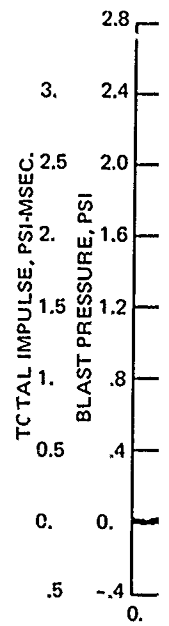
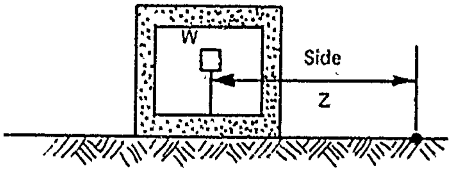
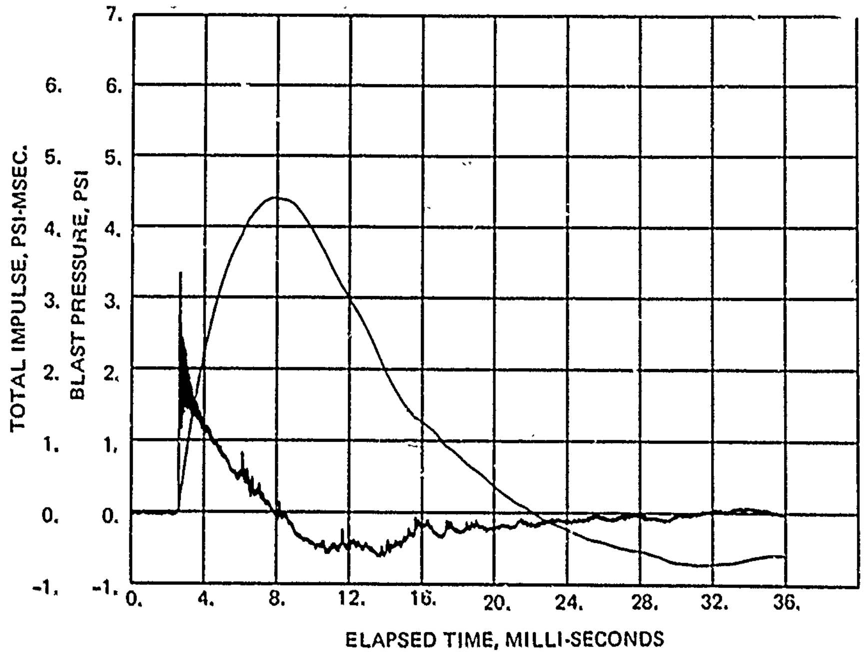


Figure A-34. Blast environme





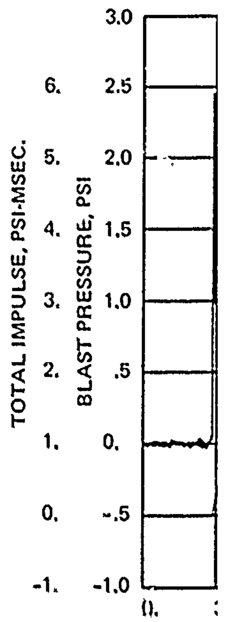
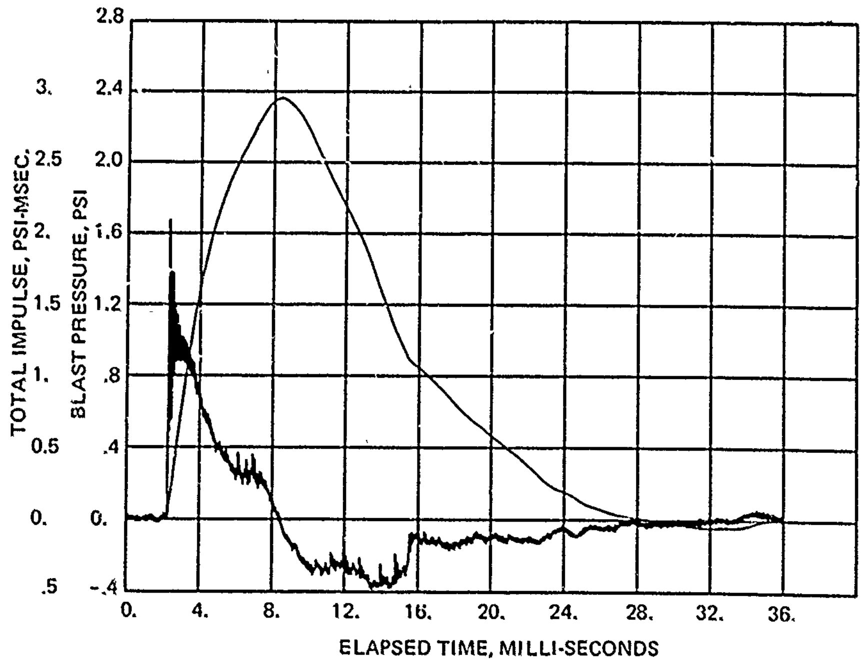


Figure A-33. Blast environment outside large 3 wall cubicle with roof. explosive charges of 1.5 pounds; Z = 28.0 ft/lb$^{1/3}$.



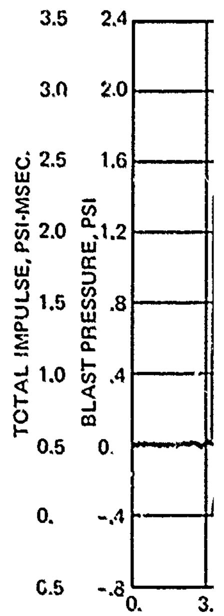
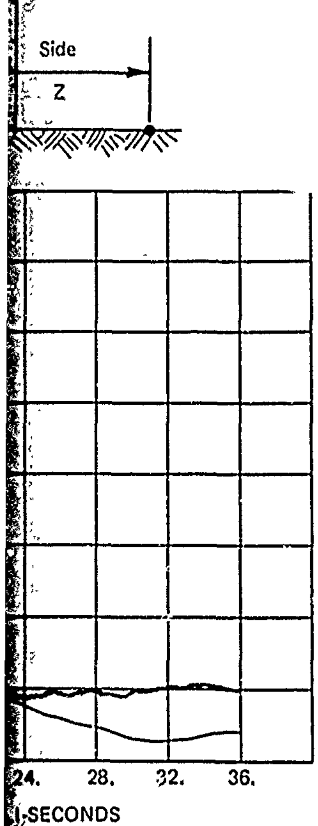
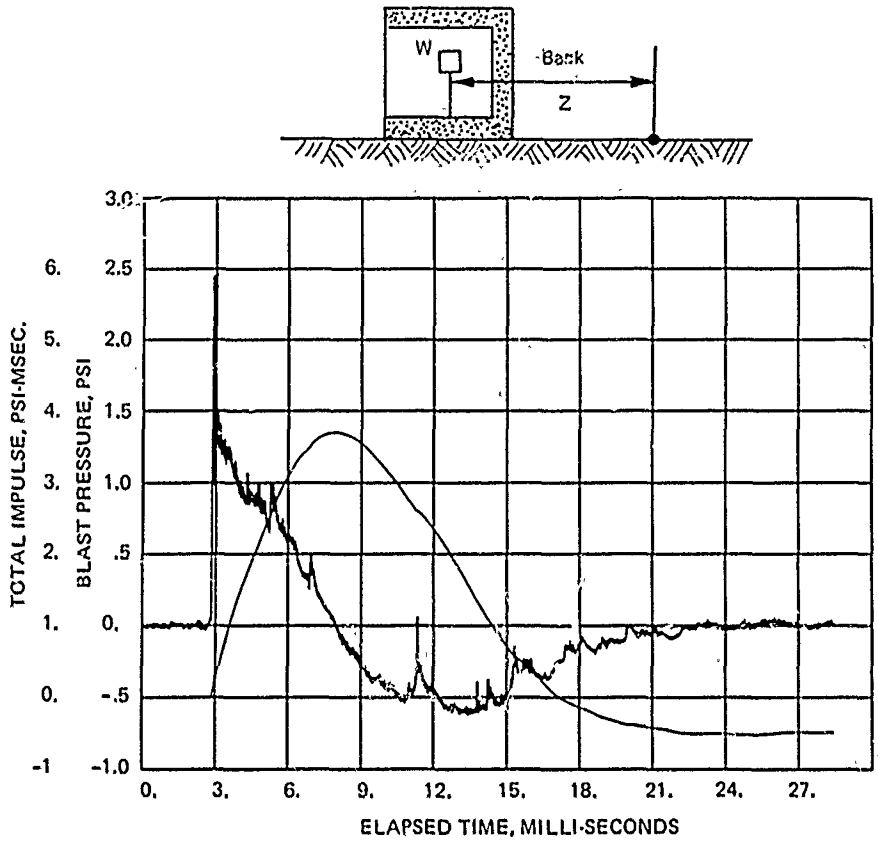
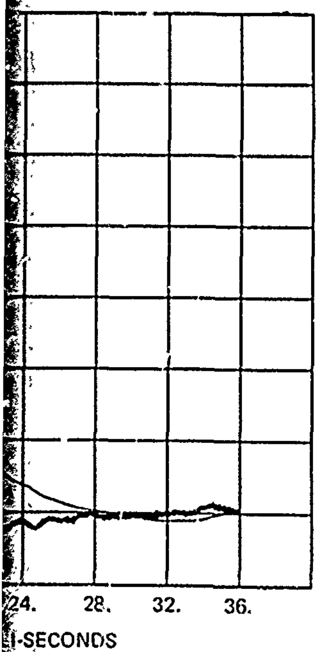


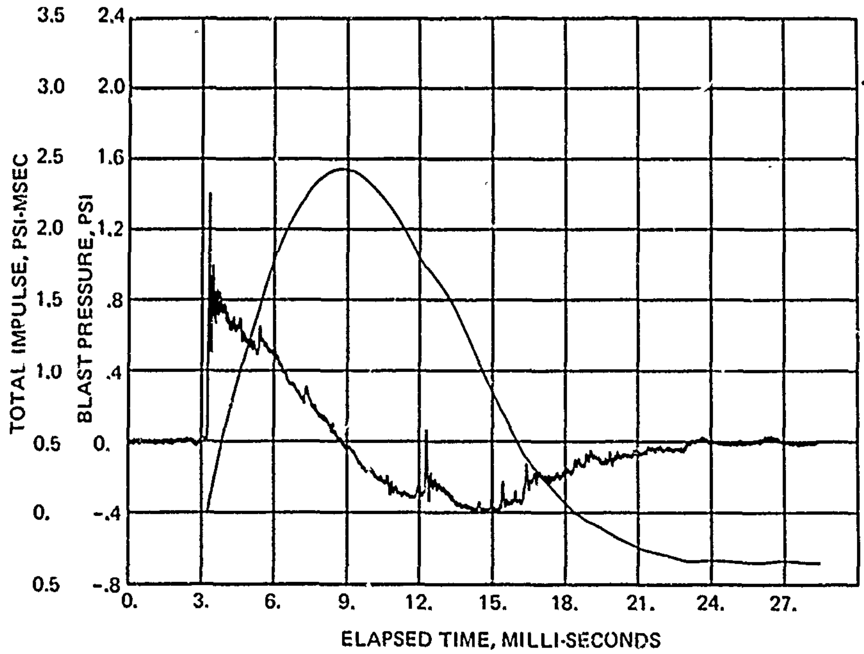
Figure A 34. Blast environment outside large 3-wall cubicle with roof. explosive charges of 1.5 pounds, Z = 43.7 ft/lb$^{1/3}$.



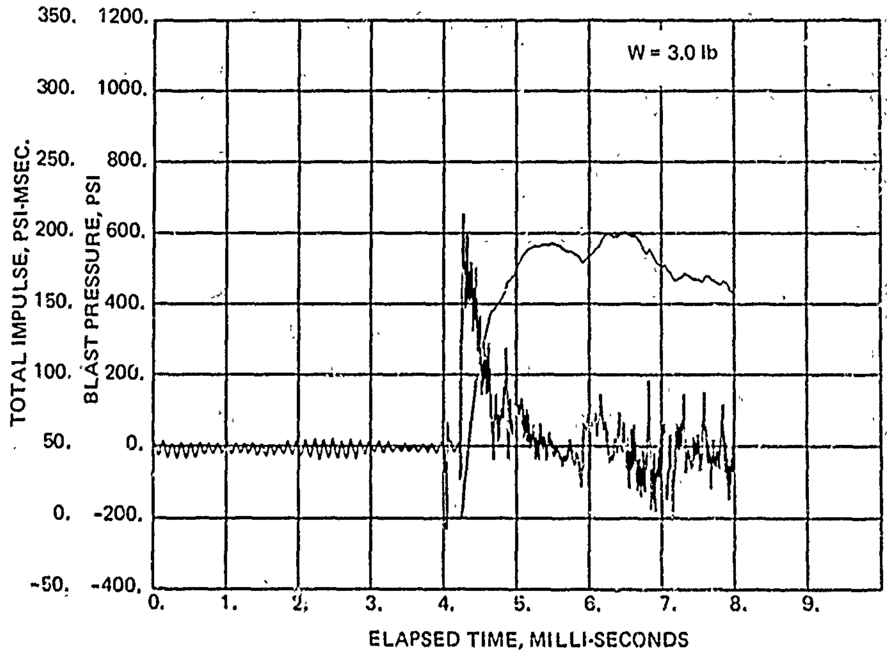


oof; explosive charges of 1.5 pounds; $Z = 28.0$ ft/lb$^{1/3}$.





f: explosive charges of 1.5 pounds; $Z = 43.7$ ft/lb$^{1/3}$.



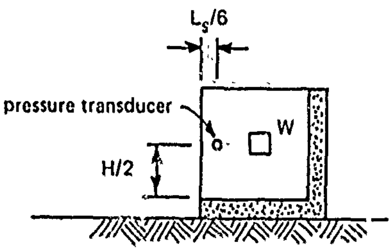


Figure A-35. Blast environment on wing wall inside large 3-wall cubicle without roof: explosive charge of 3.0 pounds.

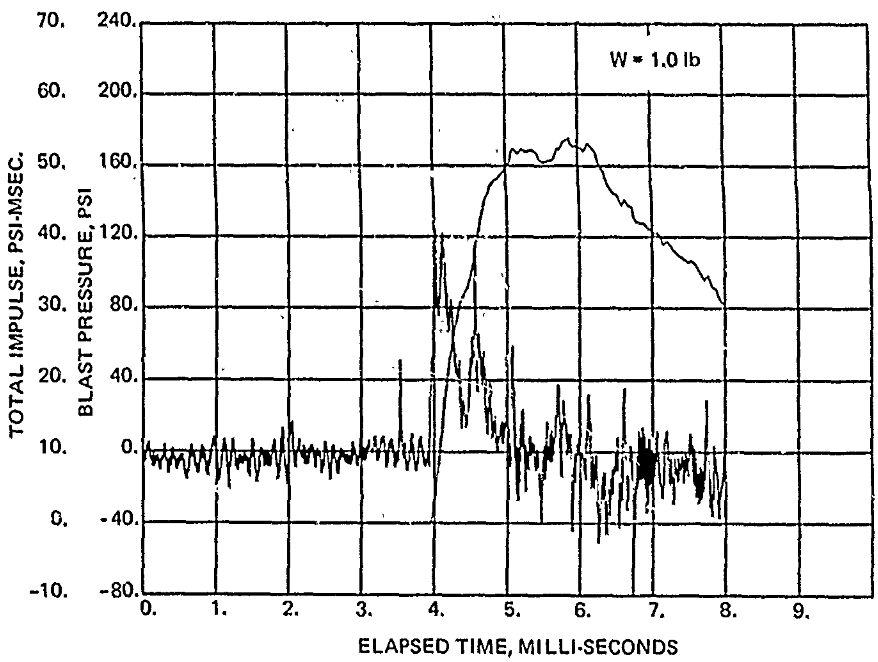


Figure A-36. Blast environment on wing wall inside large 3-wall cubicle without roof. explosive charge of 1.0 pound.

Appendix B

PEAK POSITIVE IMPULSE OUTSIDE FULLY VENTED CUBICLES

THREE-WALL CUBICLES WITHOUT ROOF

The scaled positive impulse $i_s/W^{1/3}$ behind the sidewalls, backwall and out the front of cubicles S3W and L3W are plotted versus scaled distance in Figures B1 through B6. The unconfined surface burst curve (Figure 21) in each figure serves to illustrate the effect of confining the charge inside a cubicle. The short dashed lines in each figure are best-fit straight lines for data points representing the same value of W/V.

Behind all walls, except the backwall, of both the cube- and rectangular-shaped cubicles, there is a clear influence of cubicle geometry and W/V on $i_s/W^{1/3}$. At the farther scaled distances, $i_s/W^{1/3}$ decreases with increasing W/V and $R/W^{1/3}$ according to the following equations.

Out the open front of the cube-shaped cubicle,

$$\frac{i_s}{W^{1/3}} = 110\left(\frac{W}{V}\right)^{-0.16}\left(\frac{R}{W^{1/3}}\right)^{-1.05} \qquad \text{(B-1)}$$

for $R/W^{1/3} \geq 7$ and $W/V < 2.1$

Out the open front of the rectangular-shaped cubicle,

$$\frac{i_s}{W^{1/3}} = 96.6\left(\frac{W}{V}\right)^{-0.15}\left(\frac{R}{W^{1/3}}\right)^{-1.04} \qquad \text{(B-2)}$$

for $R/W^{1/3} \geq 10$ and $W/V < 1.0$

Behind the sidewalls of both the cube- and rectangular-shaped cubicles,

$$\frac{i_s}{W^{1/3}} = 71\left(\frac{W}{V}\right)^{-0.09}\left(\frac{R}{W^{1/3}}\right)^{-0.95} \qquad \text{(B-3)}$$

for $R/W^{1/3} \geq 20$ and $W/V < 1.0$

Behind the backwall of the cube- and rectangular-shaped cubicles there is no clear trend in the impulse data or clear influence of W/V or cubicle geometry.

Note that the lines described by Equations B-1, B-2, and B-3 are nearly parallel to the curve representing an unconfined surface burst. Therefore, a critical value of W/V exists, according to Equations B-1, B-2, and B-3, such that $i_s/W^{1/3}$ outside the cubicle is identical to that from an unconfined surface burst. For any value of W/V greater than this critical value, the line relating $i_s/W^{1/3}$ and $R/W^{1/3}$ should fall, it seems, on the unconfined surface burst curve. For this reason, an upper limit for W/V is noted for Equations B-1, B-2, and B-3.

At small scaled distances, the $i_s/W^{1/3}$ curves bend over and peak out in a manner similar to the P_{so} curves. For points close outside the open front (Figures B-1 and B-2), the curves bend over and tend to merge with the unconfined surface burst curve. This probably occurs because the reflected shock waves have not yet reached and reinforced the primary detonation wave. Behind the sidewalls and backwall, the impulse curves (Figures B-3 through B-6) bend over and peak, but there appears to be no consistent relationship between the peak and W/V or the cubicle geometry.

The following problem and its solution illustrates the use of the impulse curves.

Problem. A rectangular-shaped, 3-wall cubicle contains 3,375 pounds of composition B explosive. The walls are 10 feet high. The sidewalls and backwall are 20 and 40 feet long, respectively. What is the peak positive pressure, P_{so}, positive impulse, i_s, and the effective duration t_o', at a point 300 feet from the charge behind the sidewall?

Solution. Given W = 3,375 pounds, V = 10 x 20 x 40 = 8,000 ft^3 and R = 300 feet. Therefore, $R/W^{1/3} = 300/(3,375)^{1/3} = 20$ and $W/V = 3,375/8,000 = 0.42$. From Figure 37, P_{so} = 4 psi. From Equation B-3, $i_s/W^{1/3} = 71\ (0.42)^{-0.09}\ (20)^{-0.95} = 4.46$ or $i_s = 4.46\ (3,375)^{1/3} = 66.9$ psi-msec. For design purposes, the fictitious duration of the pressure is $t_o' = 2i_s/P_{so} = 2\ (66.9)/4 = 33.5$ msec.

THREE-WALL CUBICLES WITH ROOF

The scaled positive impulse $i_s/W^{1/3}$ behind the sidewalls, backwall and outside the open front are plotted versus $R/W^{1/3}$ in Figures B-7 through B-12. Included in each figure is the unconfined surface burst curve to show the effect of confining the charge inside the cubicle. The short dashed lines in each figure are best-fit straight lines for data points representing the same value of W/V.

Behind all walls of both the cube- and rectangular-shaped cubicles, there is a clear influence of cubicle geometry and W/V on $i_s/W^{1/3}$. At larger scaled distances, $i_s/W^{1/3}$ decreases with increasing W/V and $R/W^{1/3}$ according to the following equations.

Out the open front of the cube-shaped cubicle,

$$\frac{i_s}{W^{1/3}} = 386\left(\frac{W}{V}\right)^{-0.16}\left(\frac{R}{W^{1/3}}\right)^{-1.33} \qquad \text{(B-4)}$$

for $R/W^{1/3} \geq 10$ and $W/V < 5.0$

Out the open front of the rectangular-shaped cubicle,

$$\frac{i_s}{W^{1/3}} = 263\left(\frac{W}{V}\right)^{-0.23}\left(\frac{R}{W^{1/3}}\right)^{-1.34} \qquad \text{(B-5)}$$

for $R/W^{1/3} \geq 10$ and $W/V < 0.6$

Behind the sidewalls of both the cube- and rectangular-shaped cubicles,

$$\frac{i_s}{W^{1/3}} = 55\left(\frac{W}{V}\right)^{-0.13}\left(\frac{R}{W^{1/3}}\right)^{-0.96} \qquad \text{(B-6)}$$

for $R/W^{1/3} \geq 20$

Behind the backwall of the cube- and rectangular-shaped cubicles (Figures B-11 and B-12), there is a clear influence of W/V and cubicle geometry on $i_s/W^{1/3}$, but the influence cannot be expressed in a simple mathematical form. Note that behind the backwall of the cube, $i_s/W^{1/3}$ at all scaled distances is less than $i_s/W^{1/3}$ from an unconfined surface burst.

At small scaled distances, $i_s/W^{1/3}$ curves decrease after reaching a limiting value in a manner similar to the P_{so} curves. For points close to the open front (Figures B-7 and B-8), the curves bend over and tend to merge with the unconfined surface burst curve. This reduction is attributed to the distance that the shock waves reflecting off the sidewalls and backwall must travel before they reach and reinforce the primary detonation wave. Behind the sidewalls and backwall, the impulse curves (Figures B-9 through B-12) decrease after reaching a limiting value, but there appears to be no consistent relationship between the peak and W/V or the cubicle geometry.

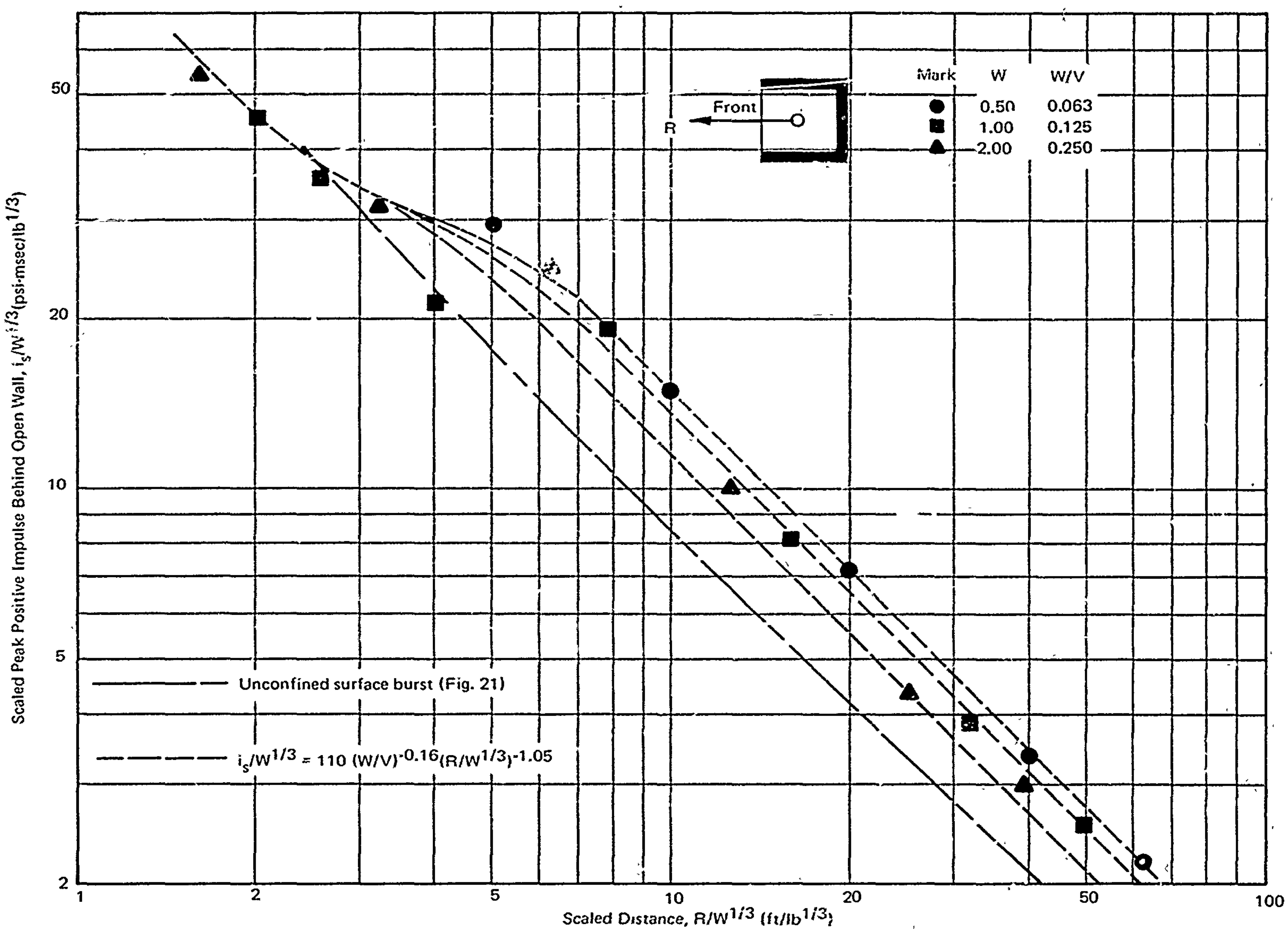


Figure B-1. Scaled peak positive impulse out the open front of small 3-wall cubicle without roof.

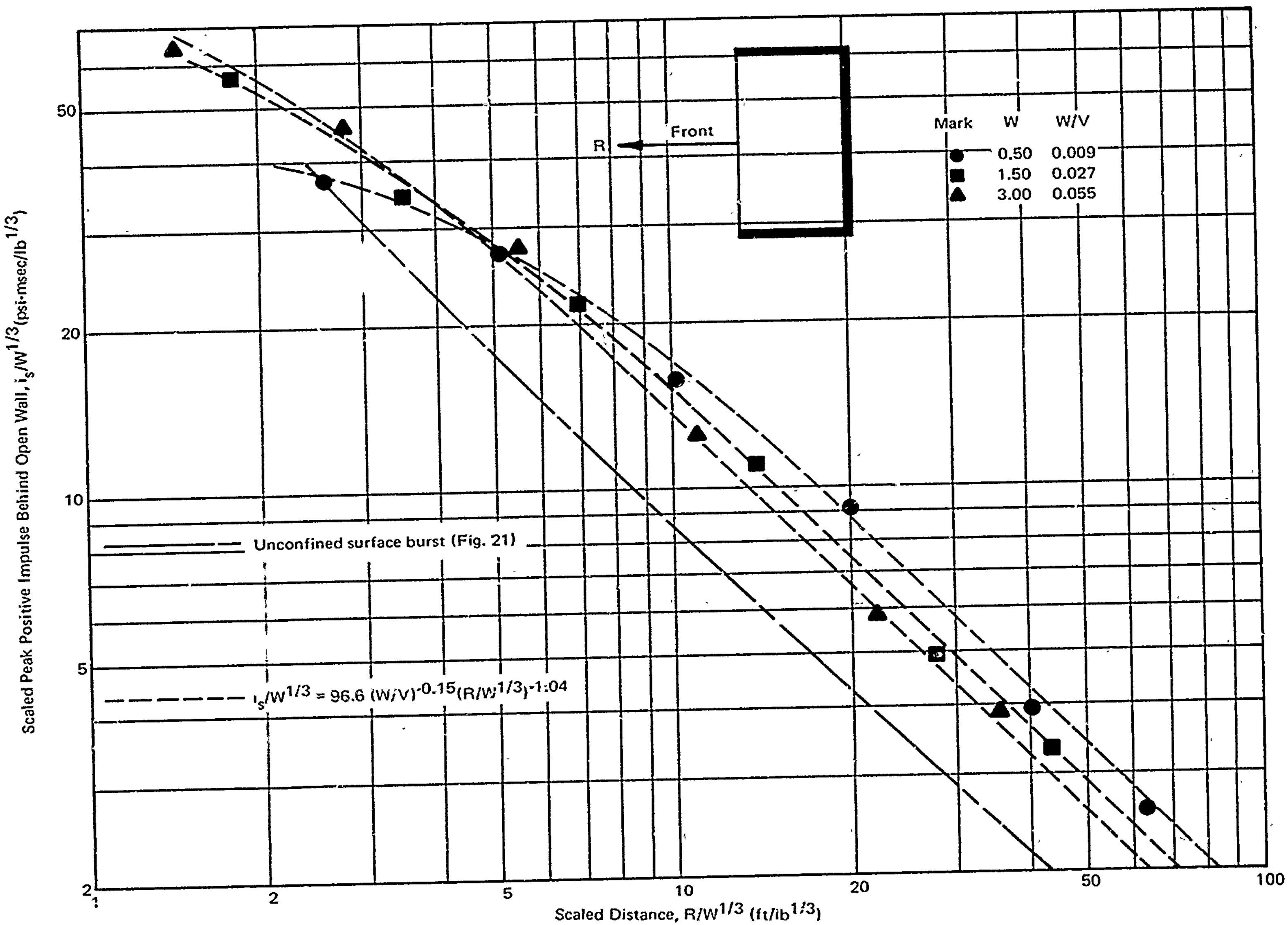


Figure B-2. Scaled peak positive impulse out the open front of large 3-wall cubicle without roof.

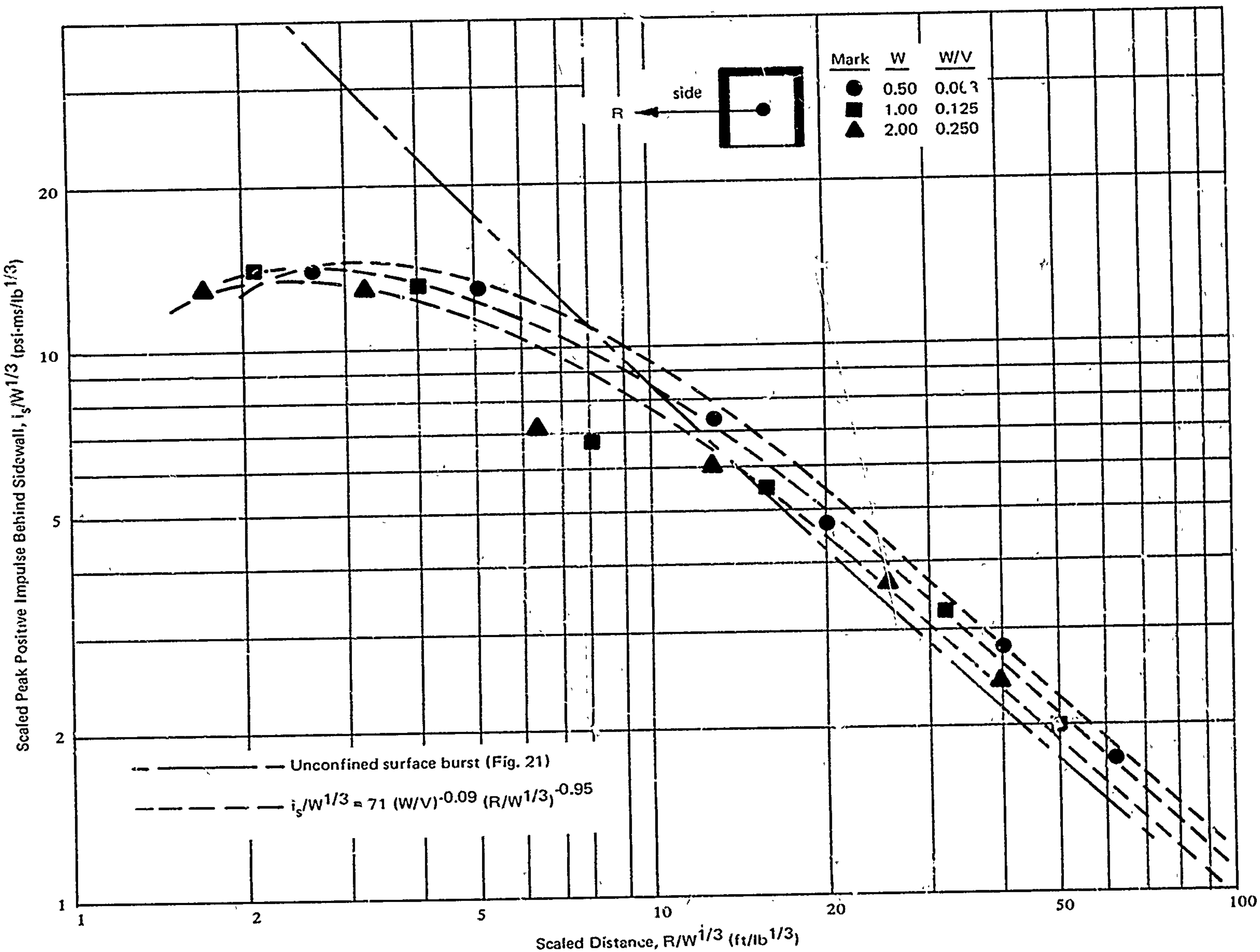


Figure B-3. Scaled peak positive impulse behind sidewall of small 3-wall cubicle without roof.

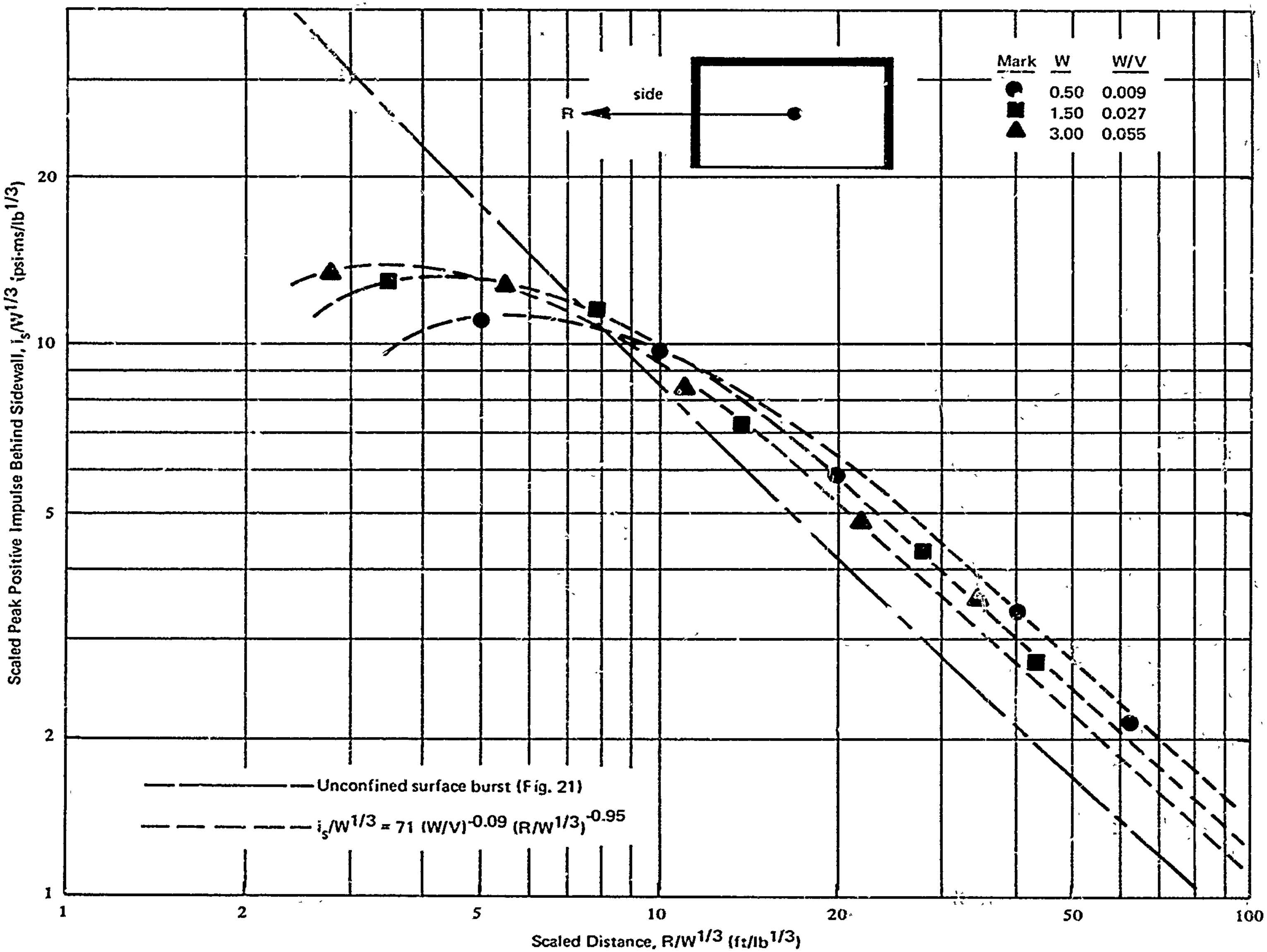


Figure B-4. Scaled peak positive impulse behind sidewall of large 3-wall cubicle without roof.

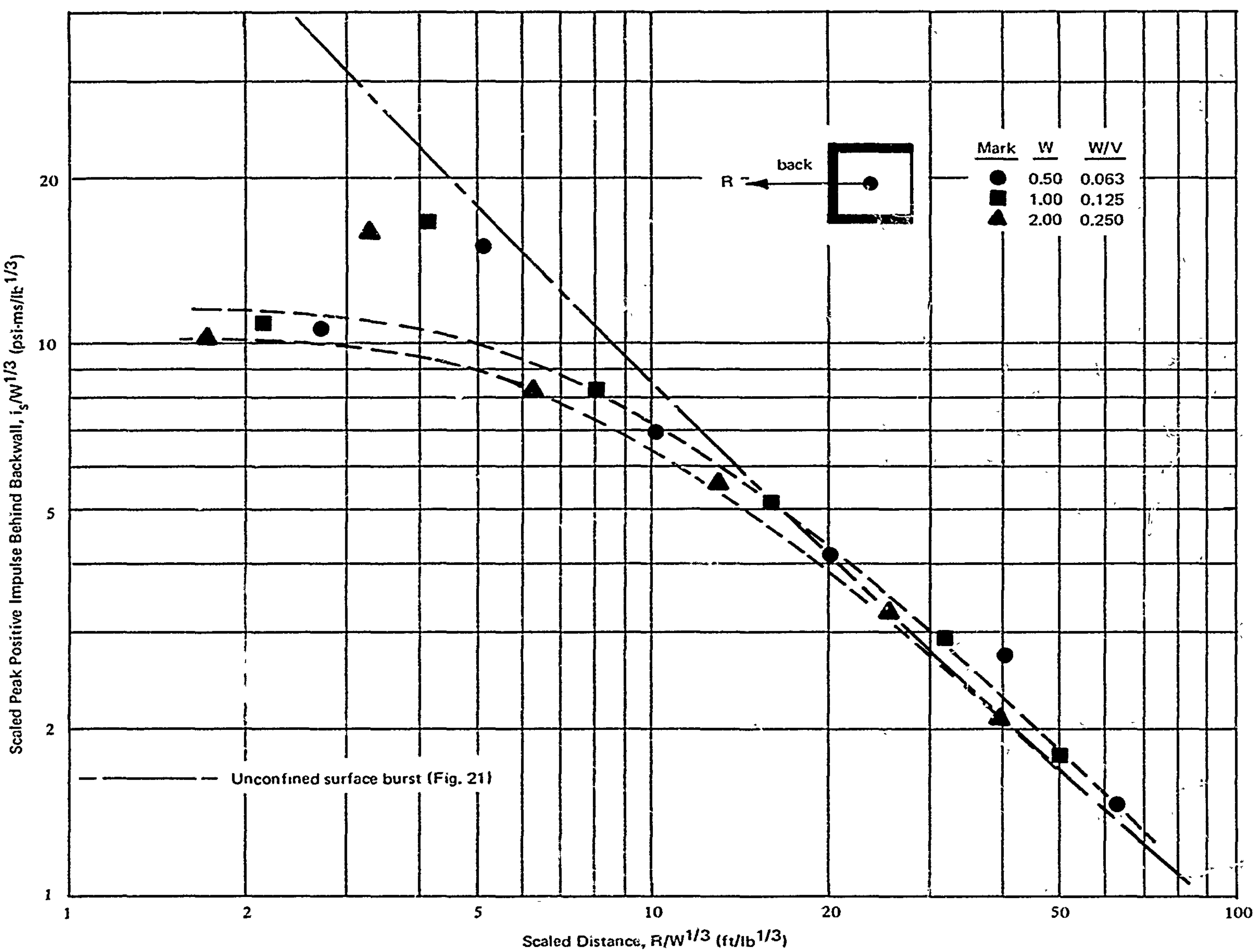


Figure B-5. Scaled peak positive impulse behind backwall of small 3-wall cubicle without roof.

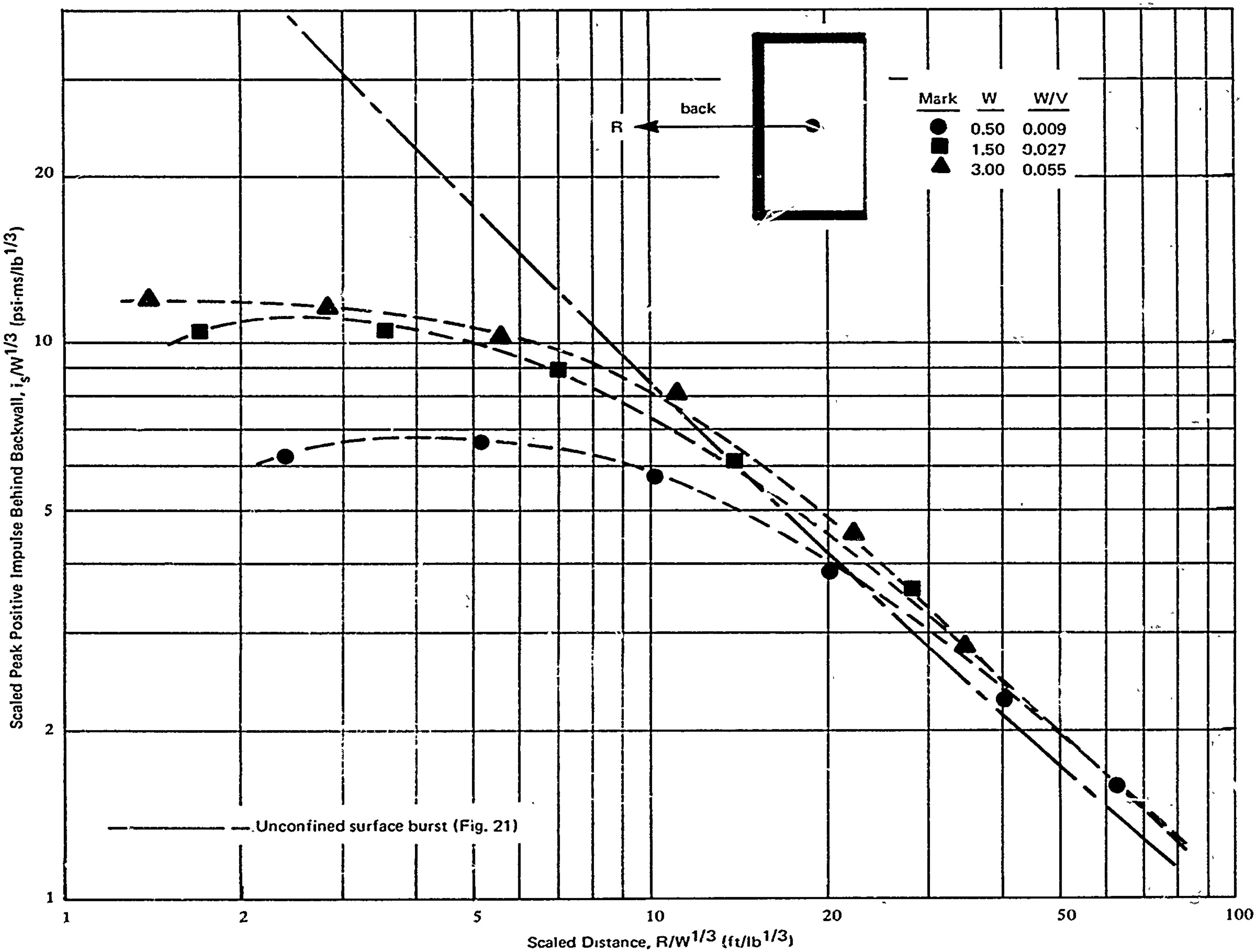


Figure B-6. Scaled peak positive impulse behind backwall of large 3-wall cubicle without roof.

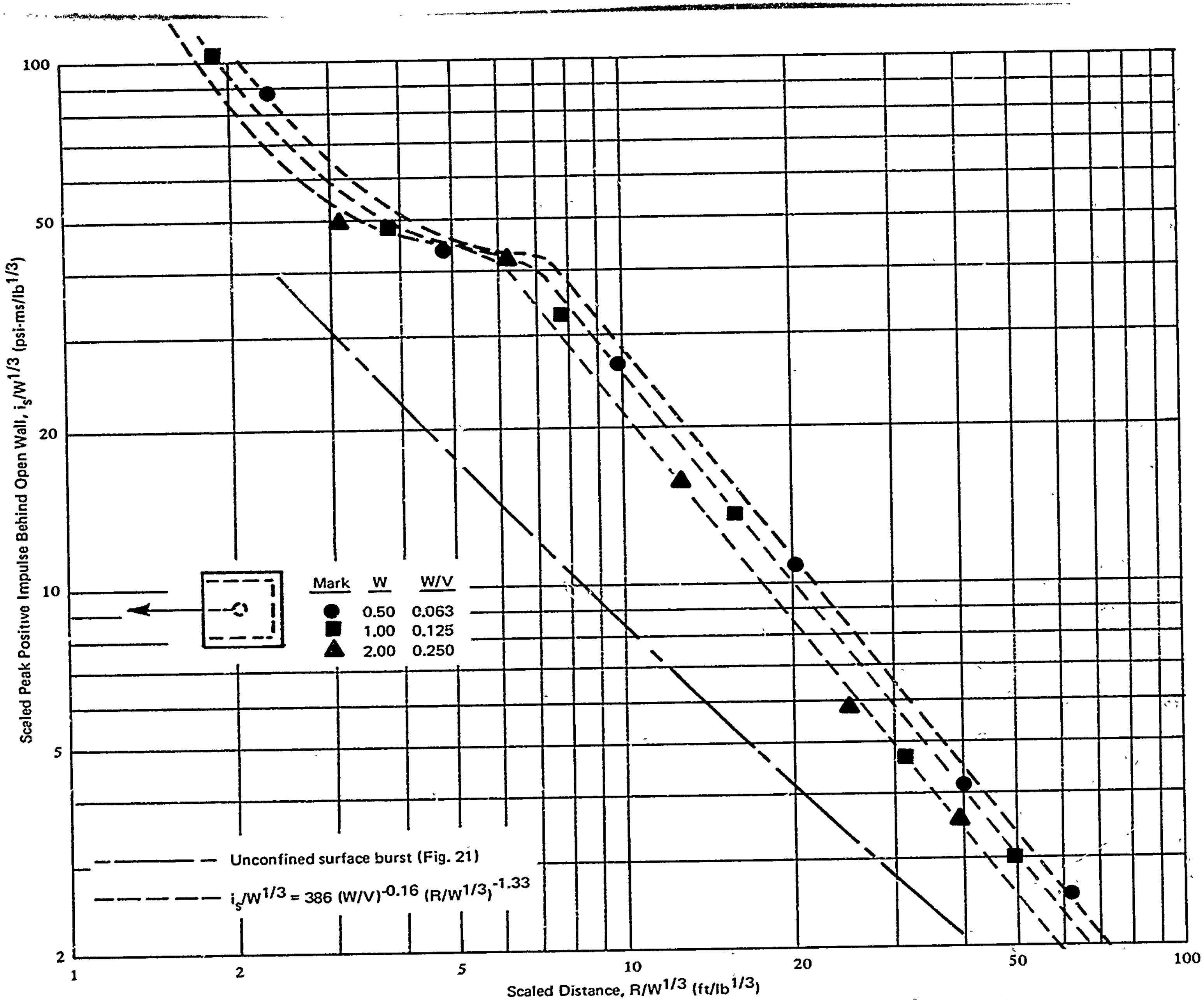


Figure B-7. Scaled peak positive impulse out the open front of small 3-wall cubicle with roof.

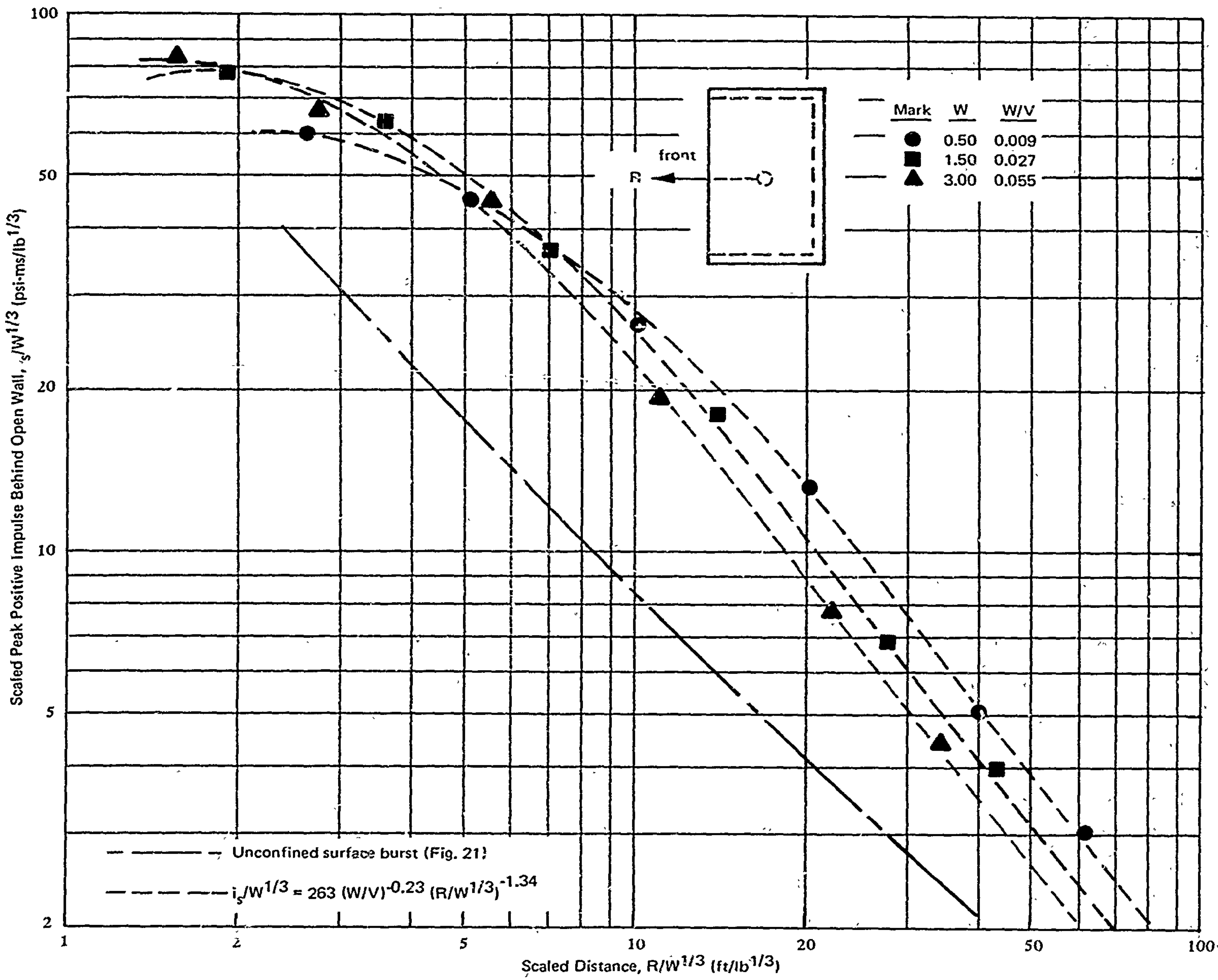


Figure B-8. Scaled peak positive impulse out the open front of large 3-wall cubicle with roof.

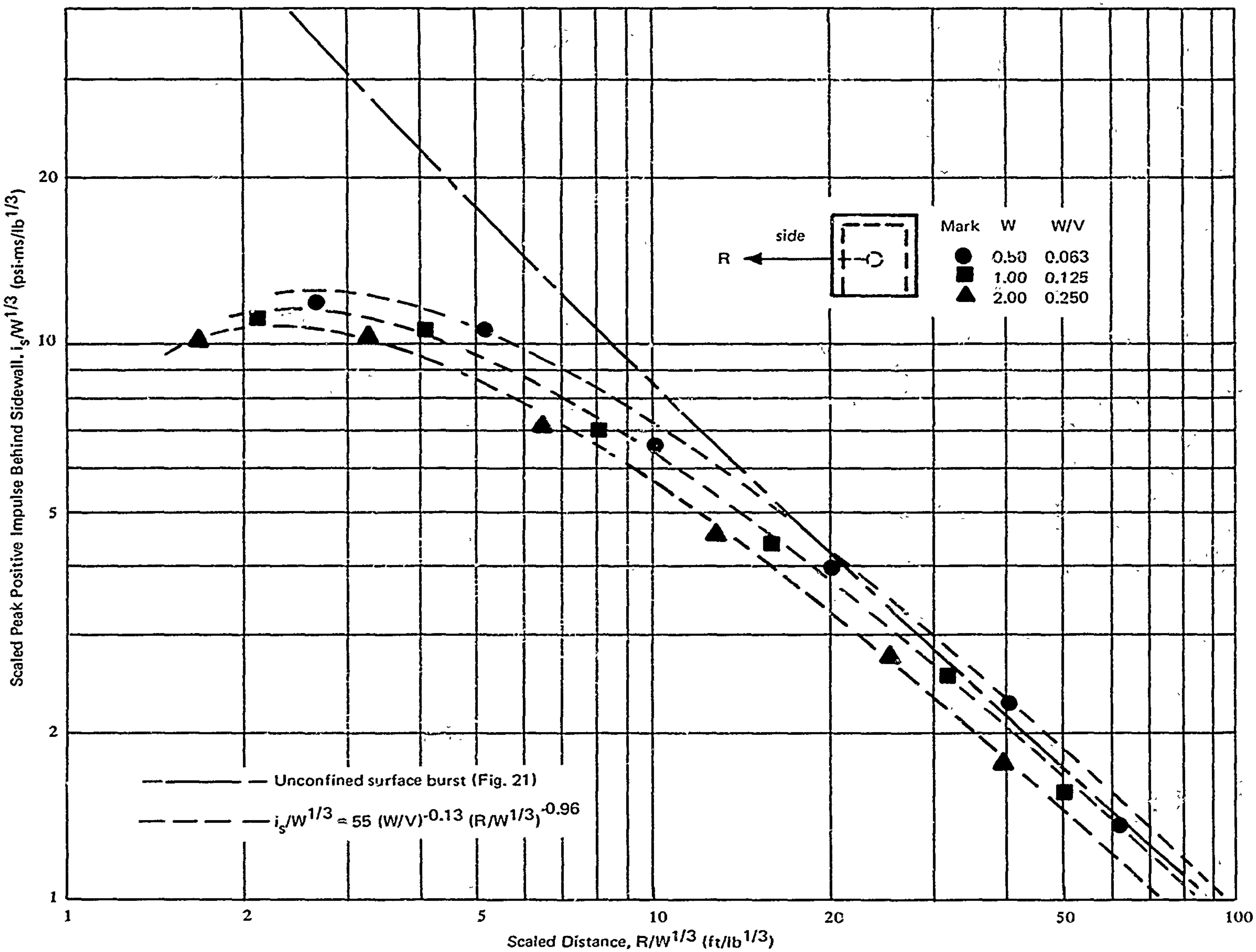


Figure B-9. Scaled peak positive impulse behind sidewall of small 3-wall cubicle with roof.

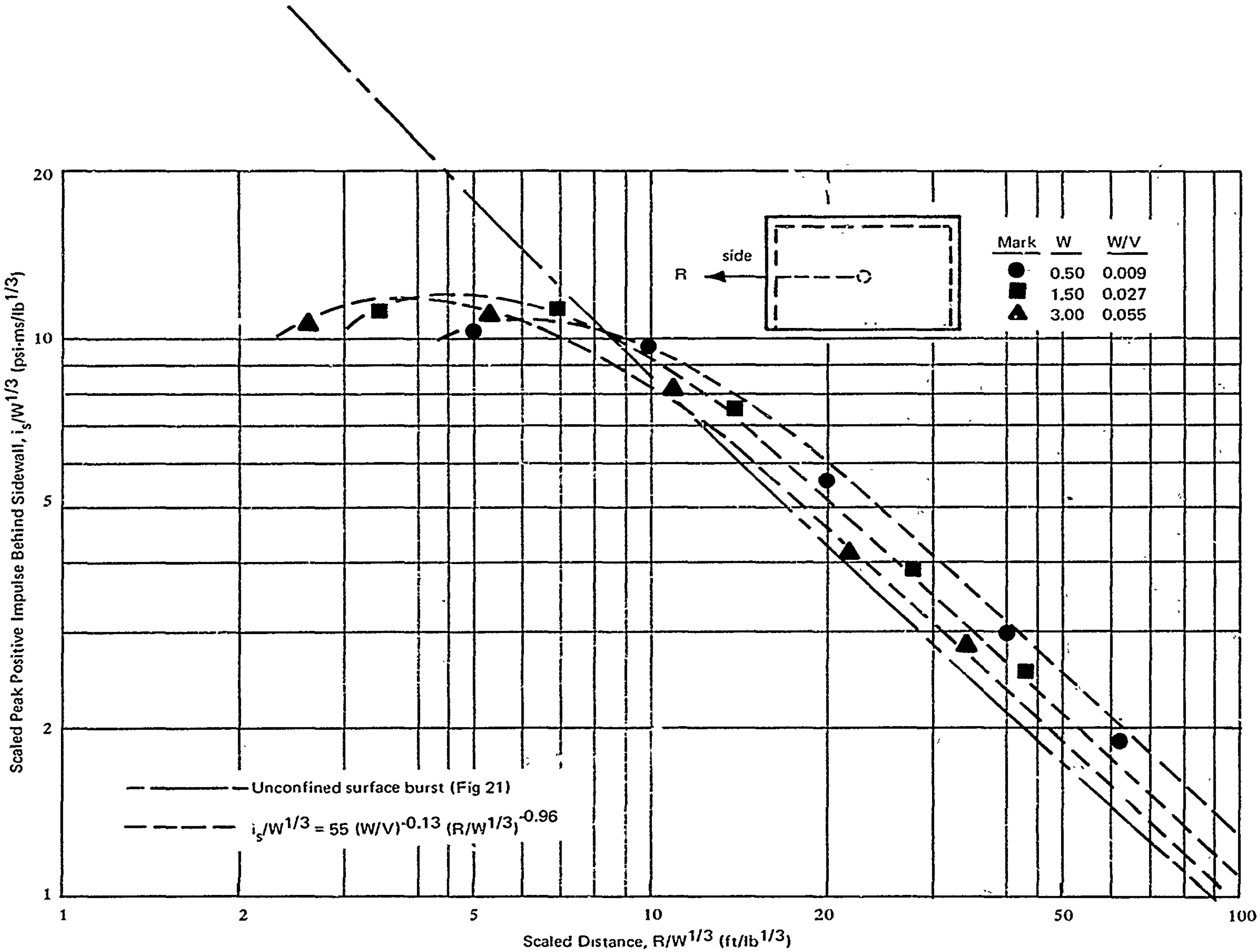


Figure B-10. Scaled peak positive impulse behind sidewall of large 3-wall cubicle with roof.

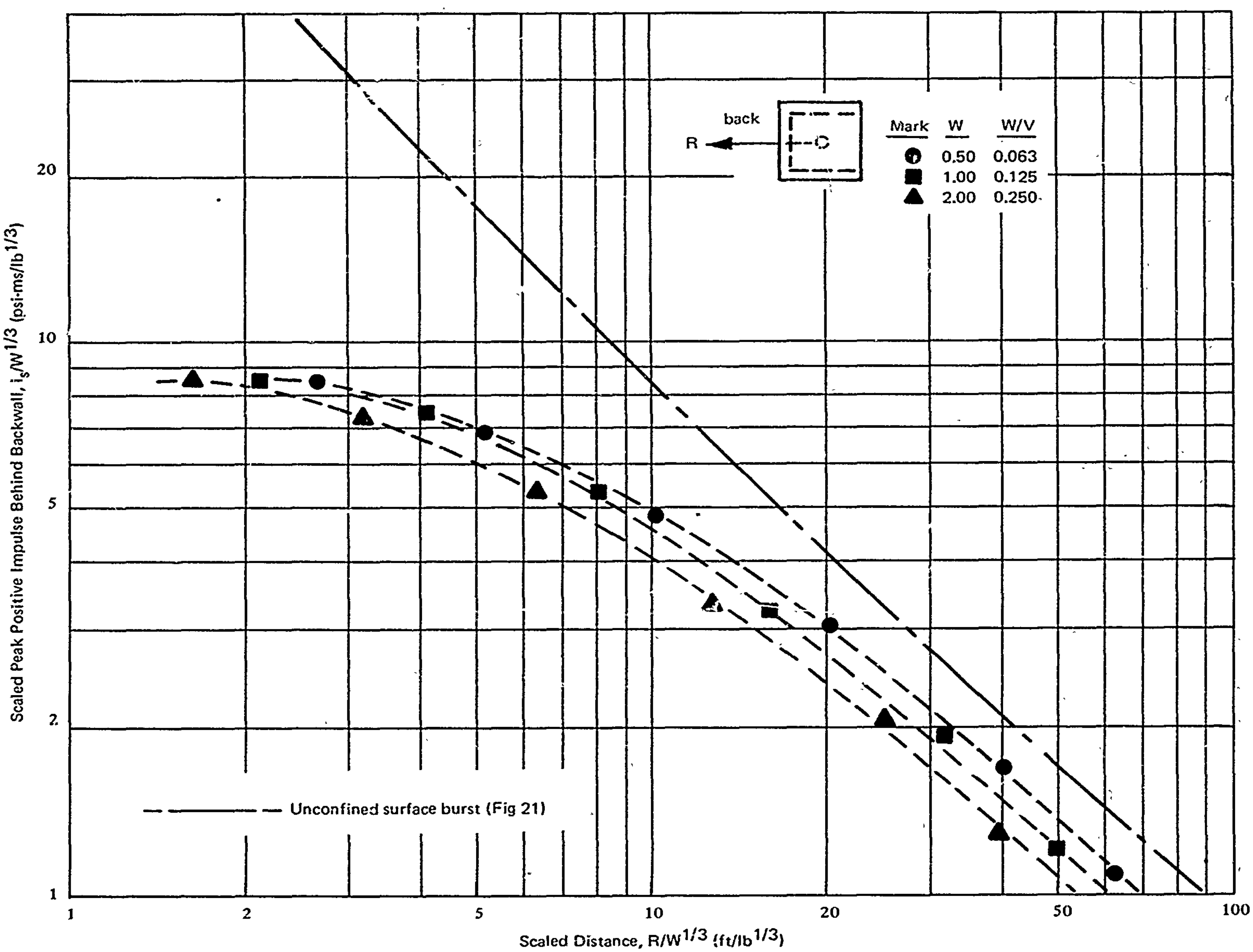


Figure B-11. Scaled peak positive impulse behind backwall of small 3-wall cubicle with roof.

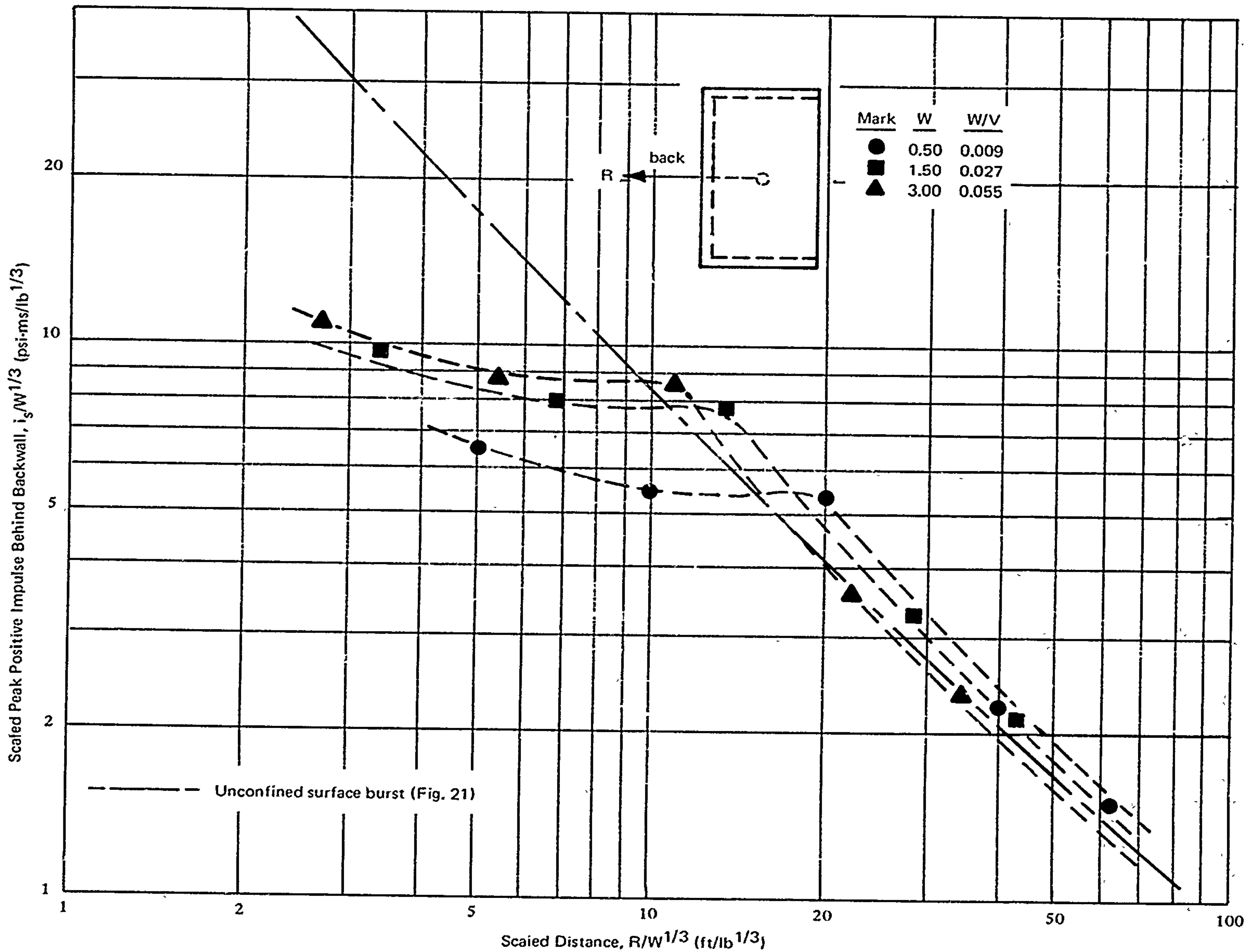


Figure B-12. Scaled peak positive impulse behind backwall of large 3-wall cubicle with roof.

Appendix C

A SEMI-EMPIRICAL PROCEDURE FOR PREDICTING THE BLAST ENVIRONMENT CLOSE BEHIND WALLS OF A CUBICLE

INTRODUCTION

Consider the peak pressures behind a sidewall of the 3-wall cubicle shown in Figure C-1. The configuration and size of the cubicle and the position and weight of the charge are fixed. The difference in elevation between the top of the sidewall and the ground surface is h. According to the curves in Figure B-2, the peak-pressure/scaled-distance curve for h = H will be similar to curve B in Figure C-1. According to the curves in Figure 20, the peak-pressure/scaled-distance curve for h = 0 will rise continuously with decreasing scaled distance in a manner described by curve A in Figure C-1. Curve A is the envelope curve shown in Figure 37 for the peak pressure behind a sidewall of a 3-wall cubicle. For $0 < h < H$, the pressure-scaled distance curve should fall somewhere below curve A and above curve B.

A semi-empirical procedure which accounts for the influence of h on peak pressures at points behind a cubicle wall is described herein. Predicted pressures correlate reasonably well with pressures measured outside some of the test cubicles. In other cases, the error is large but the general trend and shape of the predicted pressure-scaled distance curve is consistent with measured results. In all cases, the predicted pressures are closer to measured values than if the effect of h was neglected.

PROCEDURE

The envelope curve (h = 0) must be known for the particular cubicle configuration being studied. The envelope curve for a 3-wall cubicle is the appropriate curve in Figures 37 or 38. For a 4-wall cubicle with a given $A/V^{2/3}$ the envelope curve is the plot of P_{so} versus $R/W^{1/3}$ obtained from Figure 22.

Given the envelope curve, the procedure involves calculating an adjusted scaled distance $R'/W^{1/3}$ to the point of interest outside the cubicle and then reading the peak pressure P_{so} from the appropriate envelope curve. The method of calculating the adjusted range R′ to points behind the sidewall of a 3-wall cubicle is illustrated in Figure C-2. Values of $R/W^{1/3}$ and $R'/W^{1/3}$ are tabulated in Figure C-2 for cubicle S3W containing 0.5, 1.0, and 2.0 pound charges. Results are correlated with test data in Figure C-3.

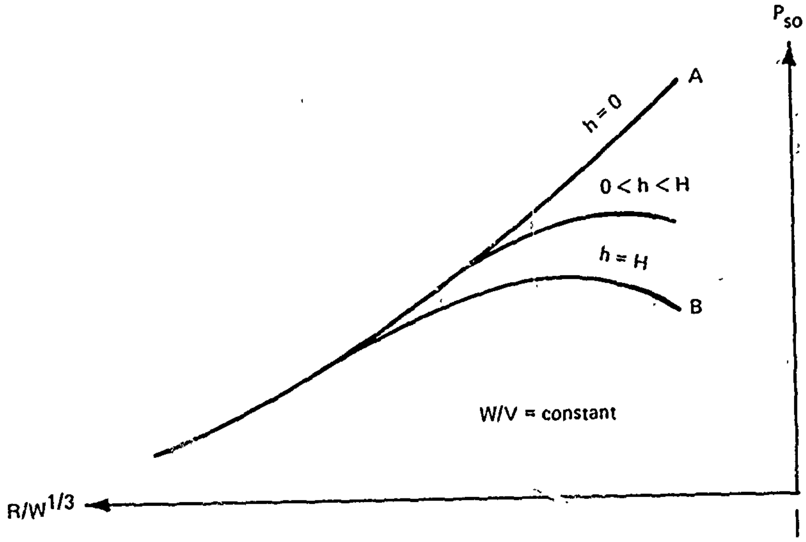
Predicted pressures are compared with pressures measured behind the sidewall of the full-scale cubicle tested in 1966 at NOTS, China Lake in Figure C-4. Measured pressures are about 20% less than predicted values for the entire range of scaled distances. This difference may be attributed to the fact that the predicted pressures are based on cylindrical charges (L/D = 1) while the NOTS data is based on spherical charges.

The NOTS data in Figure C-4 shows no peaking out of the leakage pressure curve behind the wall; leakage pressures tend to increase continuously with decreasing scaled distance. The CEL procedure indicates this would indeed be the case (see Figure C-4) because the charge densities in the NOTS tests were so large (W/V = 0.25, 0.375 and 0.55 lb/ft^3). For these large charge densities, the procedure indicates the leakage pressure curves would peak out for $R/W^{1/3} < 2.5$ ft/lb$^{1/3}$ (Figure C-4); but NOTS pressure transducers were never located closer than 5.1 ft/lb$^{1/3}$, so the phenomenon could never be detected from the NOTS data.

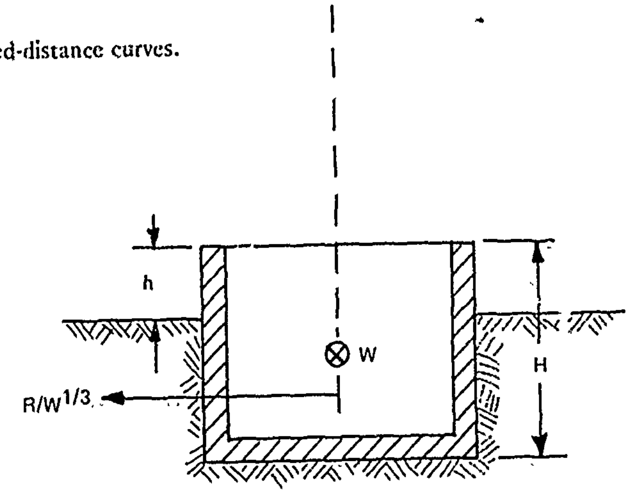
The procedure indicates that pressures close behind cubicle walls are very sensitive to h, the vertical distance from the top of the wall to the horizontal plane of interest. For example, if the ground surface outside the cubicle was at the elevation of the top of the wall (h = 0) then $R' \cong R$ so pressures would increase continuously with decreasing scaled distance in accordance with the appropriate curve in Figure 20 for a 4-wall cubicle and Figure 37 for a 3-wall cubicle.

The reduction in pressure behind a cubicle wall for $h > 0$ is attributed to the formation of a vortex, which is a region of air spinning about an axis at a high speed with low overpressures existing at its center because of the venturi effect. The vortex forms

at the leading edge of the wall (Figure 26). The vortex grows in size and apparently distorts the shock front enough to decrease substantially the pressures on the plane of interest at scaled distances close to the cubicle. The maximum range R at which the vortex reduces pressures depends, according to the procedure, on the cubicle configuration and h. The maximum range of vortex effects is independent of W; with increasing W, the predicted curves in Figures C-3 and C-4 peak out at a decreasing scaled distance $R/W^{1/3}$, but at the same absolute distance $R = d_1 + t_w + 2h$. At points corresponding to R greater than about 3 wall heights (3h) from the wall, the procedure gives pressures that are essentially the same on any horizontal plane between $h = H$ and $h = 0$.

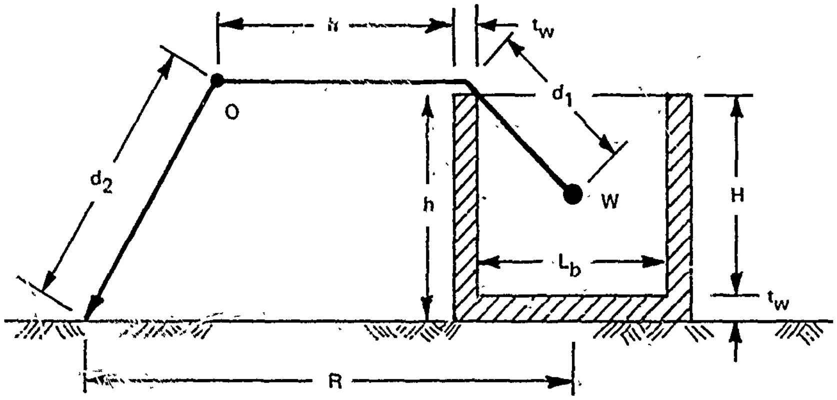


(a) Peak pressure/scaled-distance curves.



(b) Front view of a 3-wall cubicle.

Figure C-1. Influence of h on the pressure/scaled-distance curve for points behind a wall.



$R' = d_1 + t_w + h + d_2$

where d_2 = slant distance from point O to point of interest on the ground surface at range R from the charge

$L_s = 2.00$; $H = 2.00$; $t_w = 0.25$

R (ft)	R' (ft)	W = 0.50		W = 1.0		W = 2.0	
		$R/W^{1/3}$	$R'/W^{1/3}$	$R/W^{1/3}$	$R'/W^{1/3}$	$R/W^{1/3}$	$R'/W^{1/3}$
2	6.61	2.51	8.32	2	6.61	1.58	5.24
3	6.21	3.78	7.82	3	6.21	2.38	4.93
4	6.21	5.04	7.82	4	6.21	3.17	4.93
5	6.61	6.30	8.32	5	6.61	3.96	5.24
8	8.94	10.08	11.26	8	8.94	6.35	7.10
10	10.79	12.56	13.59	10	10.79	7.93	8.56
14	14.64	17.63	18.45	14	14.64	11.11	11.62
20	20.56	25.20	25.90	20	20.56	15.87	16.32
40	40.47	50.40	50.99	40	40.47	31.75	32.12

Figure C-2. Adjusted scaled distance for points behind sidewall of 3-wall cubicle with h equal to H.

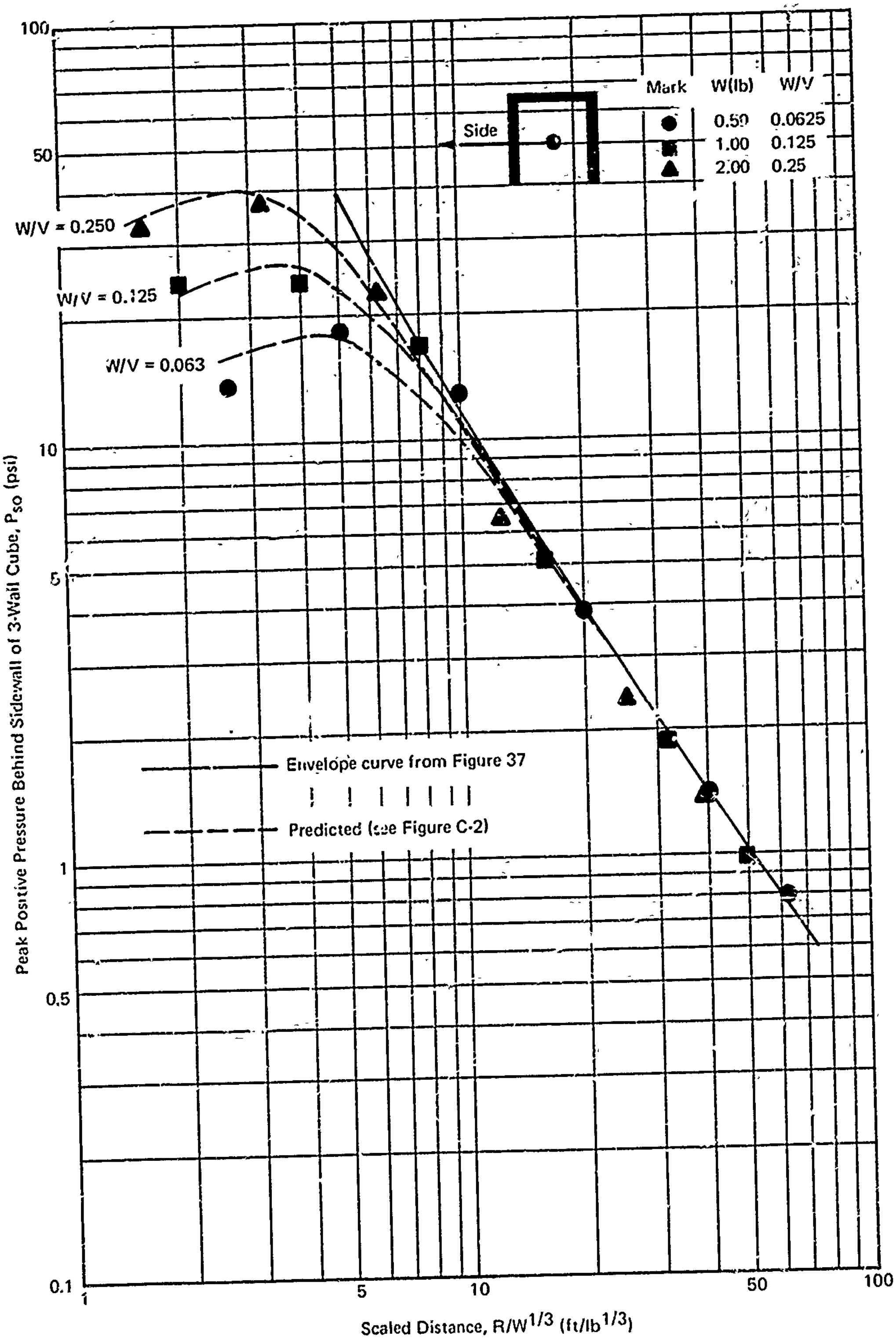


Figure C-3. Predicted and measured pressures behind sidewall of 3-wall cubicle without roof.

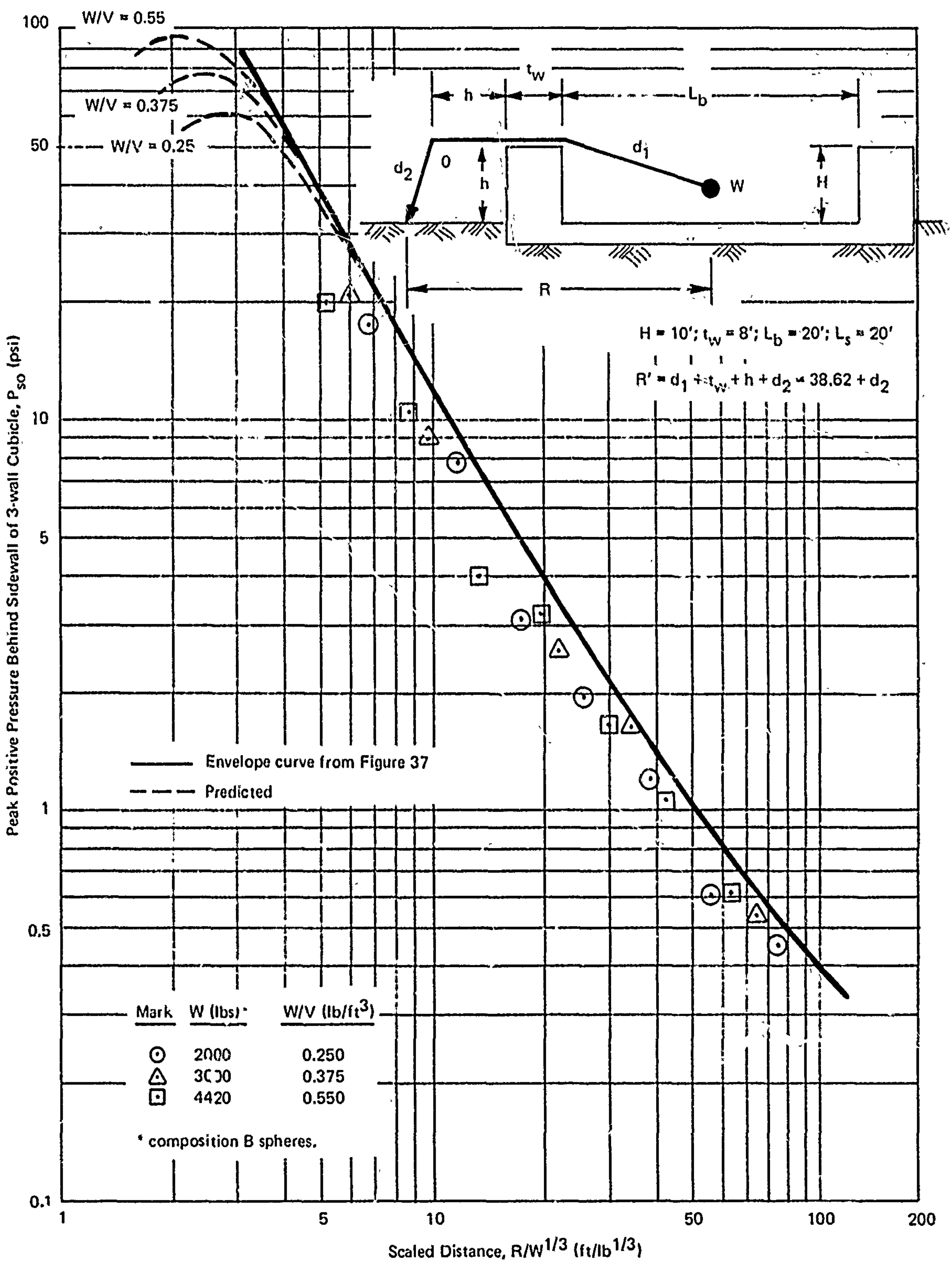


Figure C-4. Predicted and measured pressures behind sidewall of full-scale, 3-wall cubicle tested at NOTS [10].

REFERENCES

1. Department of the Army, Navy, and Air Force. Design Manual Army TM5-1300, NAVFAC P-397, and AFM-88-22: Structures to resist the effects of accidental explosions. Washington, DC, Jun 1969.

2. Picatinny Arsenal. Technical Report 4168: Full and model scale tests of bay structures, by Stuart Levy, et al. Dover, New Jersey, Feb 1971.

3. William S. Filler. "Post-detonation pressure and thermal studies of solid high explosives in a closed chamber," in Proceedings of Sixth Symposium (International) on Combustion, New York, Reinhold, 1957, p. 648.

4. J. F. Proctor and W. S. Filler. "A computerized technique for blast loads from confined explosions," from Minutes of the 14th Annual Explosives Safety Seminar, New Orleans, Louisiana, Nov 1972, p. 99.

5. Hans R. W. Weibull. "Pressures recorded in partially closed chambers at explosion of TNT charges," Annals, New York Academy of Sciences, Vol. 152, Oct 1968, pp. 357-361.

6. Naval Civil Engineering Laboratory. Technical Report R-70: Determination of blast leakage pressures and fragment velocity for fully vented and partially vented protective cubicles, by John M. Ferritto. Port Hueneme, California, Dec 1972.

7. ———. Technical Proposal: Design of frangible covers for cubicles containing explosives, by W. A. Keenan and J. E. Tancreto. Port Hueneme, California, May 1973.

8. Office of Scientific Research and Development, National Defense Research Committee. Effects of impact and explosion, volume 1. Washington, DC, 1946.

9. Ballistics Research Laboratory. BRL Memorandum Report No. 1536: A study of flow patterns in aircraft revetments, by George Teel and George Coulter. Aberdeen, Maryland, Feb 1964.

10. Civil Engineering Laboratory. Technical Note N-1390: Effects of charge shape and composition B on blast environment, by James E. Trancreto. Port Hueneme, California, May 1975.

LIST OF SYMBOLS

A Total vent area of the cubicle, ft^2

A_r Vent area in roof of cubicle, ft^2

A_w Vent area in walls of cubicle, ft^2

D Diameter of cylindrical charge or opening in roof, ft

d_1 Distance from charge to top of wall or roof, ft

H Interior height of cubicle wall from floor to roof, ft

h Vertical distance from floor to center of gravity of charge; vertical distance from top of cubicle roof, wall, or pipe stack down to ground surface or horizontal plane of interest, ft

i_g Unit impulse of gas pressure, psi-msec

i_s Unit positive incident impulse, psi-msec

$i_{\bar{s}}$ Unit negative incident impulse, psi-msec

L Length, ft

L_b Interior length of backwall or distance between sidewalls, ft

L_p Length of pipe stack, ft

L_s Interior length of sidewalls or distance between frontwall and backwall, ft

l_b Horizontal distance from backwall to center of gravity of charge, ft

l_s Horizontal distance from sidewall to center of gravity of charge, ft

N Number of adjacent reflecting surfaces

P Pressure, psi

P_g Peak positive gas pressure, psi

P_r Peak positive reflected pressure, psi

P_{so} Peak positive incident pressure, psi

$P_{\bar{so}}$ Peak negative incident pressure, psi

R Horizontal range from charge to pressure transducer or the point of interest, ft

R' Skew range from charge to pressure transducer or other point of interest, ft

T_n Effective natural period of vibration, msec

t Time, msec

t_A Time of arrival of blast wave at given point

t_g Duration of gas pressure, msec

t_o Actual duration of positive pressure phase, msec

t_w Thickness of wall, ft

t'_g $2i_g/P_g$ = fictitious duration of gas pressure, msec

t'_o Design duration of positive pressure phase, msec

$t_{\bar{o}}$ Duration of negative pressure phase, msec

V Internal volume of cubicle, $H \times L_b \times L_s$, ft

W Total weight of explosive, lb

Z $R/W^{1/3}$, scaled horizontal range from charge, $ft/lb^{1/3}$

DISTRIBUTION LIST

SNDL Code	No. of Activities	Total Copies	
–	1	12	Defense Documentation Center
–	1	15	Department of the Army, Picatinny Arsenal
FKA1C	1	3	Naval Facilities Engineering Command
FKN1	6	6	NAVFAC Engineering Field Division
FKN5	9	9	Public Works Centers
FA25	1	1	Public Works Center
–	6	6	RDT&E Liaison Officers at NAVFAC Engineering Field Divisions
–	288	291	CEL Special Distribution List No. 15 for persons and activities interested in reports on Structural Mechanics